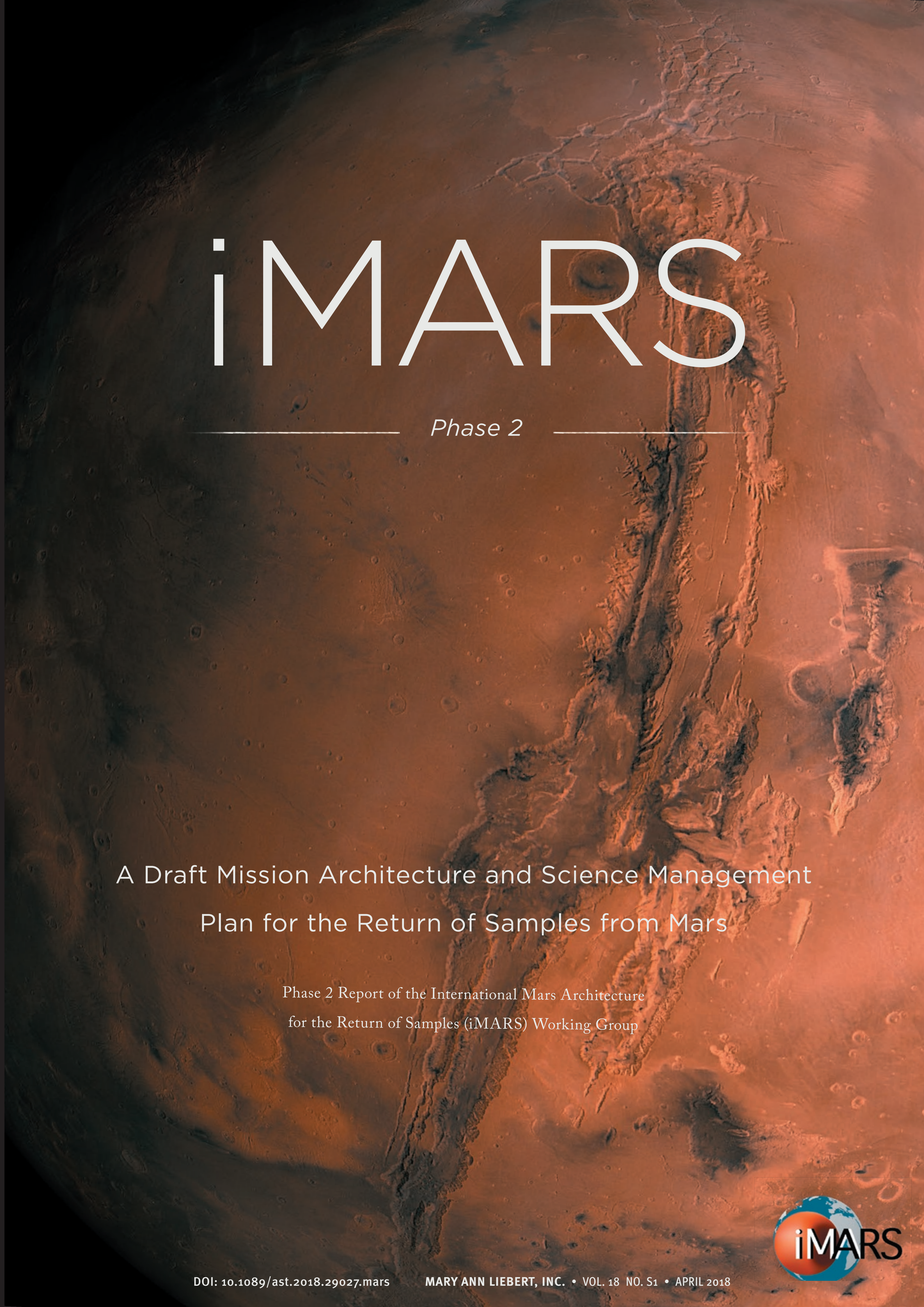

iMARS

Phase 2

A Draft Mission Architecture and Science Management Plan for the Return of Samples from Mars

Phase 2 Report of the International Mars Architecture for the Return of Samples (iMARS) Working Group

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COVER IMAGE

Mars Global View of Valles Marineris. Mosaic of the Valles Marineris hemisphere of Mars projected into point perspective, a view similar to that which one would see from a spacecraft. The distance is 2500 kilometers from the surface of the planet, with the scale being .6km/pixel. The mosaic is composed of 102 Viking Orbiter images of Mars

Image credit: NASA/JPL-Caltech

iMARS

Phase 2

A Draft Mission Architecture and Science Management Plan for the Return of Samples from Mars

Phase 2 Report of the International Mars Architecture for the Return of Samples (iMARS) Working Group

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IMAGE

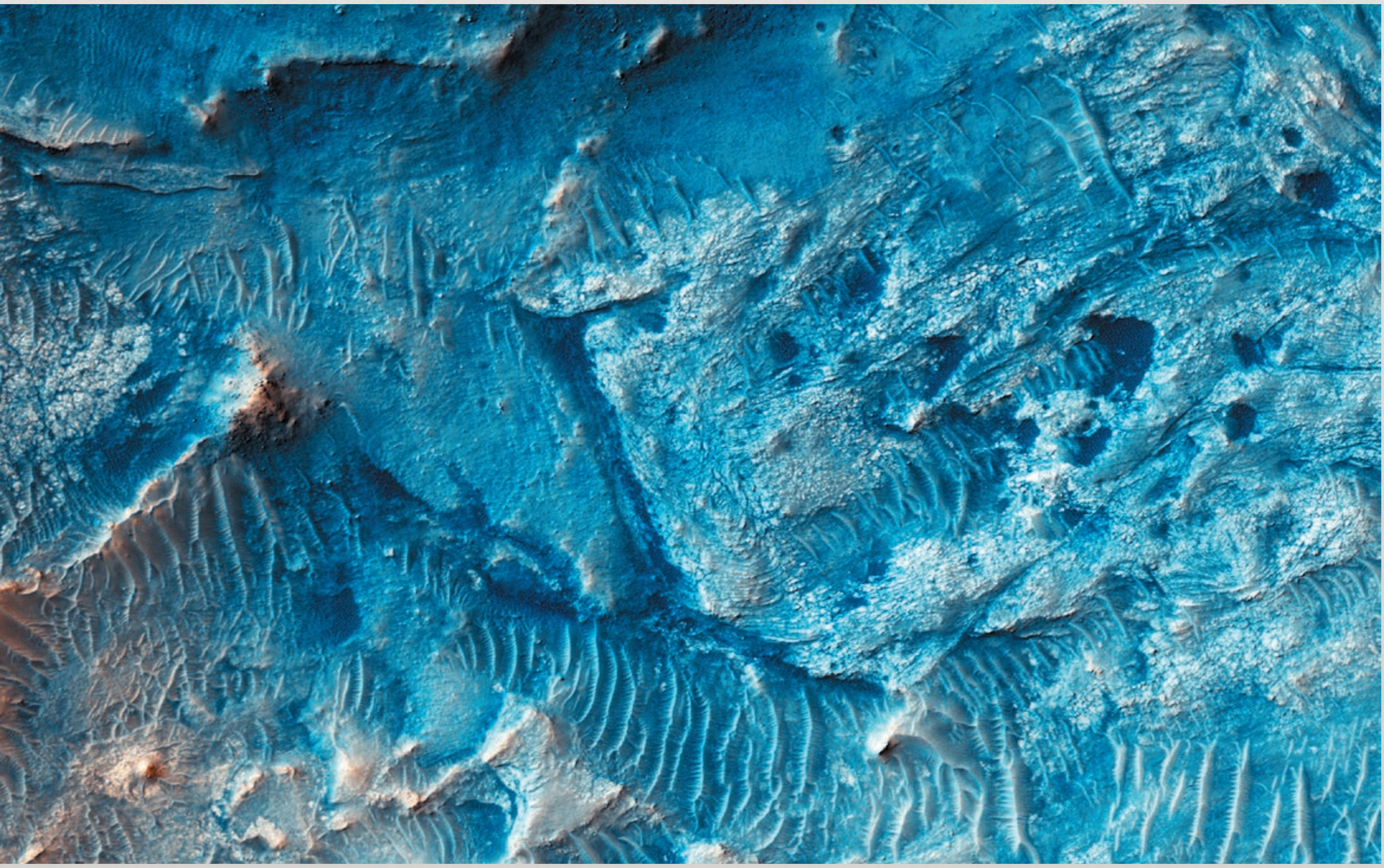
The two linear depressions in this image form part of the Elysium Fossae complex, a group of troughs located in the Elysium quadrangle of Mars. These troughs are tectonic features, likely formed by the stretching, tearing and subsequent collapse of the crust resulting from the rise of the nearby Elysium volcanic province.

Image credit: NASA/JPL-Caltech/MSSS

Preliminary Planning for an International Mars Sample Return Mission

Contents

Executive Summary



ABOVE IMAGE

An East Watershed for Jezero Crater. Jezero Crater is candidate future landing site that contains sediments deposited by at least three ancient rivers. This image was targeted to the eastern headlands of the river flowing in from that direction.

Image credit: NASA/JPL-Caltech/Univ. of Arizona

Executive Summary

The International Mars Exploration Working Group (IMEWG) was formed in 1993 to provide a forum for the international coordination of Mars exploration. In 2007, IMEWG chartered the international Mars Architecture for the Return of Samples Working Group (iMARS WG), which produced a Phase 1 report in 2008 (iMARS, 2008). In 2014, IMEWG chartered an iMARS Phase 2 Working Group, comprising two panels of experts: (i) Engineering and (ii) Science/Earth Operations. The iMARS Phase 2 WG was tasked to provide:

- A status report on planning for a Mars Sample Return (MSR) campaign, building on missions and international developments achieved since the iMARS Phase 1 WG issued its report; and
- Recommendations for progressing toward campaign implementation, including a proposed sample management plan.

This report presents the iMARS Phase 2 WG's findings. It details top-level campaign requirements that would meet stated science objectives and planetary protection constraints. It presents an updated reference MSR architecture, made of three flight elements and one ground element (termed the 3+1 architecture). It provides technical and programmatic justifications for this architecture and report also discusses alternatives to the reference architecture. The WG also reports on the status of MSR technology developments conducted by several space agencies around the world, evidence of the willingness of major space stakeholders to invest in MSR implementation. This report elaborates on programmatic considerations relating to MSR, including campaign robustness, international coordination and decision-making, a provisional implementation timeline, and a possible cost-sharing model.

In this report, the WG presents:

- A returned-sample management plan, including an organizational structure for an international Mars sample science institute that outlines roles and responsibilities of key members and describes sample return facility requirements;
- A science implementation plan, covering preliminary sample examination flow, sample allocation process, and data policies; and
- A Mars sample curation plan, including sample tracking and routing procedures, sample sterilization considerations, and long-term archiving recommendations.

The WG's key conclusions are that:

- It is feasible to return scientifically selected samples from Mars in 2031/33 under the proposed mission architecture, technology development roadmap, and sample management plan. A successful campaign will depend on early and binding agreements for long-term commitments by participating organisations.
- Returning samples from Mars will require a multidisciplinary approach. Scientific, safety and curatorial

aspects of the campaign must each be considered and integrated when developing mission architecture and sample management structure.

- While the Mars exploration community has made progress in understanding planetary protection implications of MSR and associated technology developments, important requirements and protocols remain to be further developed.

The WG's key recommendations are that:

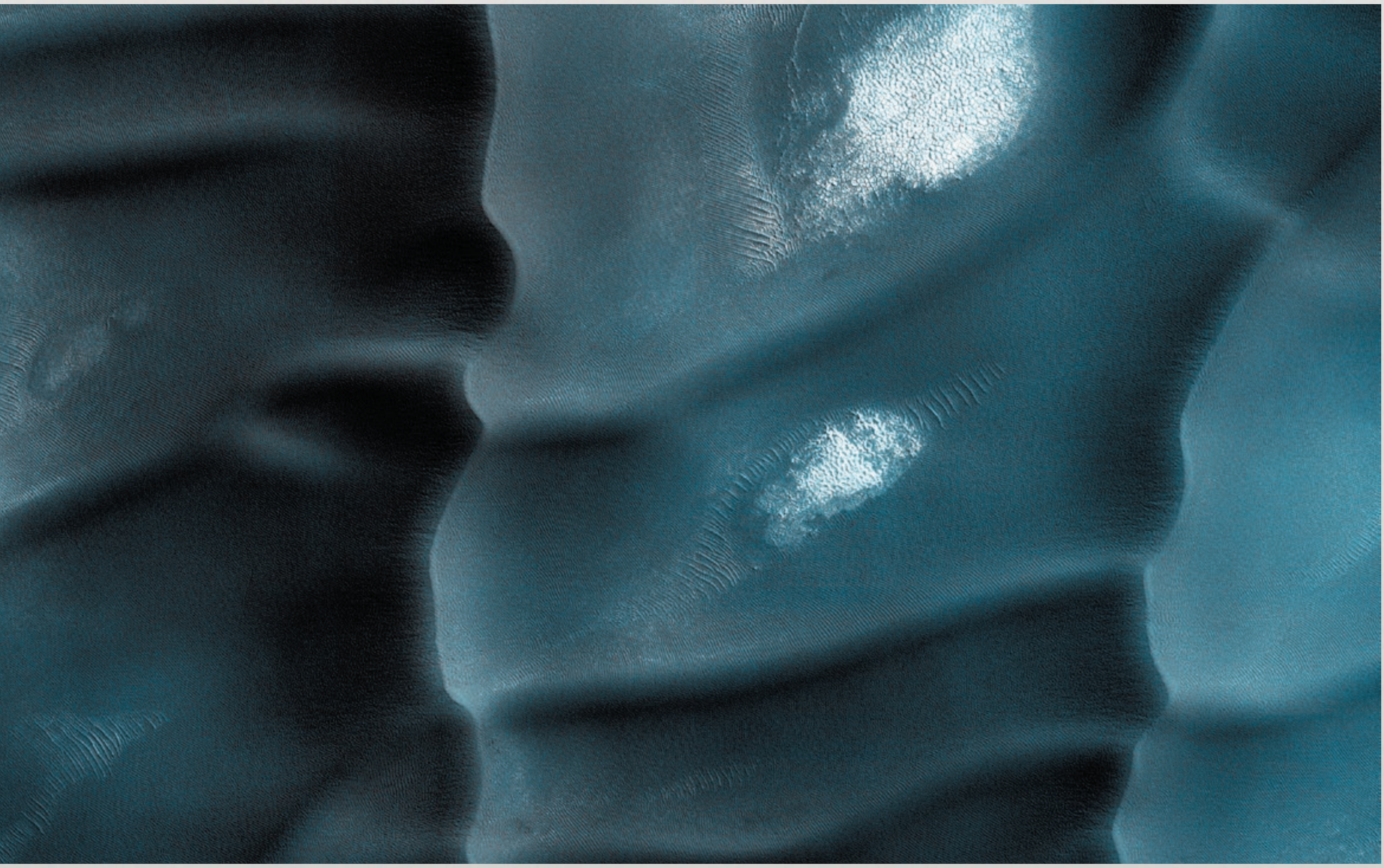
- To advance development of MSR architecture, interested international partners must declare their interests, define a cooperation framework, and determine their contributions.

- An internationally-tasked and -accepted planetary protection protocol for MSR should be produced as soon as possible, as this protocol will have technical and programmatic implications for the mission architecture.

- MSR campaign partners should establish an international MSR Science Institute as part of the campaign's governance structure upon approval to return samples from Mars.

- Two key MSR enabling technologies, the Mars ascent vehicle and sample containment ("break-the-chain-of-contact"), require further investments to proceed with development.

I. | Introduction



ABOVE IMAGE

North Polar Gypsum Dunes in Olympia Undae. These sand dunes are a type of aeolian bedform and partly encircle the Martian North Pole in a region called Olympia Undae.

Image credit: NASA/JPL-Caltech/Univ. of Arizona

iMARS

1.1 Motivation

Mars Sample Return (MSR) is key to answering some of the most fundamental questions in planetary exploration: Does life exist beyond Earth? How did the Solar System evolve? The space community has long identified MSR as a main objective of planetary exploration (iMARS Phase 1, 2008; Committee on Planetary Science Decadal Survey 2010; McLennan et al., 2012). Now international partners are at the threshold of possessing the necessary knowledge and capability to return atmospheric and surface samples from Mars to Earth.

While robotic orbiter and lander missions to Mars have demonstrated powerful remote-sensing and in-situ analytic capabilities, much more powerful and sophisticated analysis of martian samples will be possible in terrestrial laboratories. An MSR campaign will require the development of new technologies that future Solar System exploration missions can employ and help to prepare for crewed missions to the Red Planet.

The complexity and cost involved in executing an MSR campaign is too challenging for any single nation to take on alone. A collaborative international effort will be necessary. The goal of this document, developed by representatives from iMARS Phase 2 participating organisations, is to build upon previous work by presenting a feasible approach for a potential MSR campaign that would be internationally organized, funded, and conducted.

1.2 Objectives and Scope

The international Mars Architecture for the Return of Samples (iMARS) Working Group was chartered by the International Mars Exploration Working Group (IMEWG) in 2006 to develop a potential plan for an internationally sponsored and executed Mars sample return (MSR) mission. Its purpose to outline the scientific and engineering requirements of such an international mission in the 2018–2023 timeframe.

The overarching goal of the iMARS Working Group is to:

> *"Identify how international cooperation might enable sample return from Mars, document the existing state-of-knowledge on return of samples from Mars, develop international mission architecture options, identify technology development milestones to accomplish a multi-national mission, and determine potential collaboration oppor-*

> *tunities within the architecture and technology options and requirements, and current Mars sample return mission schedule estimates of interested nations. The activity will also identify specific national interests and opportunities for cooperation in the planning, design, and implementation of mission-elements that contribute to sample return. The Working Group's final product(s) is expected to be a potential plan for an internationally sponsored and executed Mars sample return mission." (iMARS WG, 2008, Appendix 1).*

The iMARS WG released its Phase 1 report in 2008. IMEWG chartered the iMARS Phase 2 Working Group in March 2014 to document major developments since 2008. This iMARS WG Phase 2 report provides an update of the Phase 1 report.

Section 2 of this report provides baselines and assumptions for an MSR campaign, including overarching science objectives and top-level campaign requirements. This section also discusses planetary protection considerations, highlighting the need for an internationally accepted protocol for preventing forward and backward contamination of returned samples.

Section 3 provides an update of MSR campaign reference architecture, describing campaign elements and considering alternative architectures. It also elaborates on key technologies required for each element and highlights critical programmatic and policy issues that must be considered for such a large international endeavour.

Section 4 outlines a sample science management plan, including a sample management structure, implementation approach and curation plan intended to maximise science return. An overriding principle underlying this plan is open science: MSR science will be openly competed, and every effort will be made to involve the public.

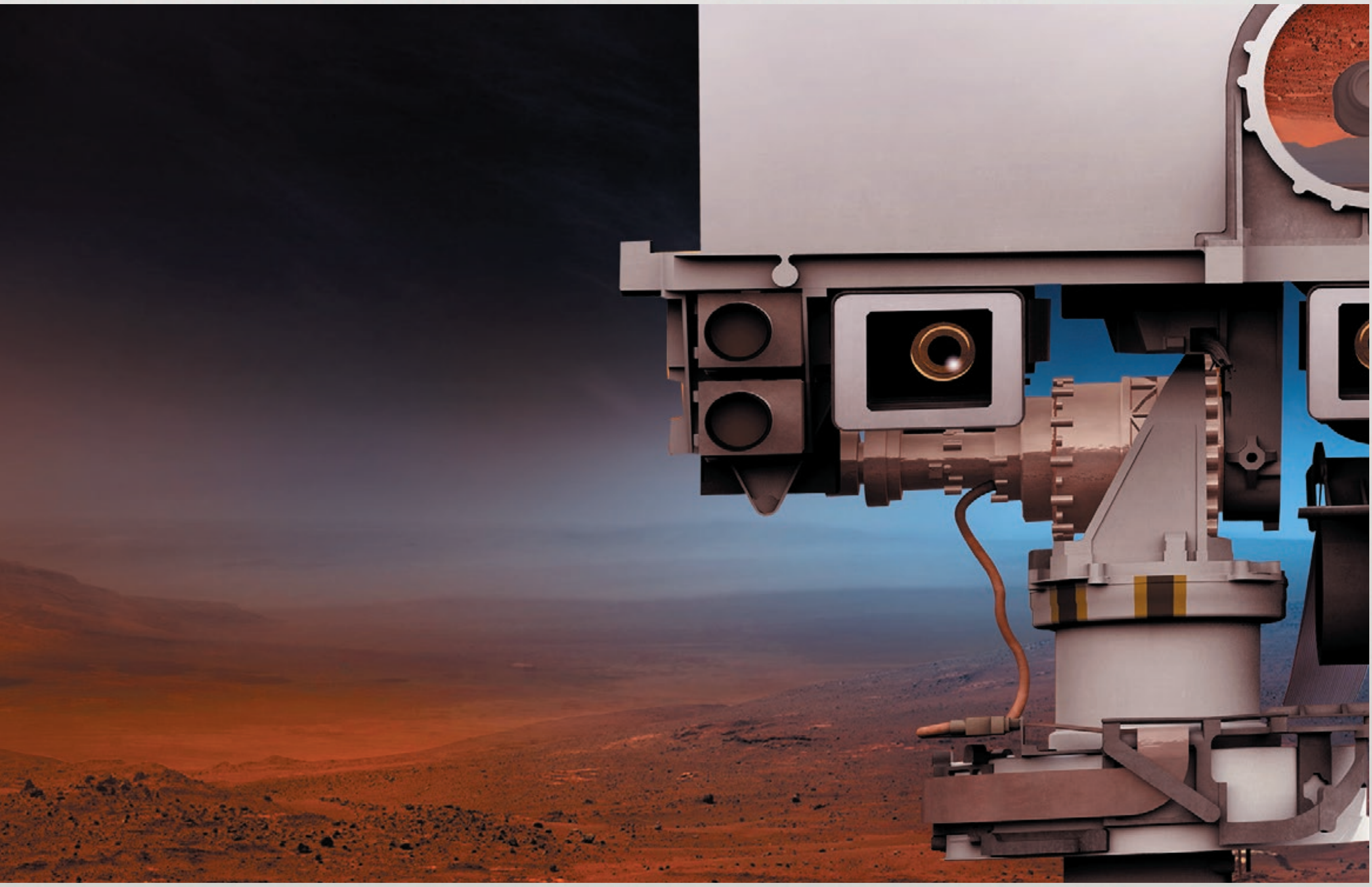
Section 5 provides conclusions and recommendations.

IMAGE

Curiosity Self-Portrait at 'Windjana' Drilling Site. NASA's Curiosity Mars rover used the camera at the end of its arm in April and May 2014 to take dozens of component images combined into this self-portrait where the rover drilled into a sandstone target called "Windjana."

Image credit: NASA/JPL-Caltech/MSSS

II. MSR Status and Assumptions



ABOVE IMAGE

NASA to Launch Mars Rover in 2020 (Artist's Concept). NASA's Mars 2020 Project will re-use the basic engineering of NASA's Mars Science Laboratory/Curiosity to send a different rover to Mars, with new objectives and instruments. This artist's concept depicts the top of the 2020 rover's mast.

Image credit: NASA/JPL-Caltech

iMARS

This section starts with a summary of MSR reference mission architecture described in the 2008 iMARS WG Phase 1 report and then provides a high-level summary of advances made since 2008. The iMARS WG was not tasked in Phase 2 with developing science drivers or objectives for an MSR campaign. Thus, science objectives outlined by the MSR End-to-End International Science Analysis Group (McLenan et al., 2011) are used as a baseline.

2.1 Summary of iMARS Phase 1 Reference Architecture

The reference mission architecture described in the iMARS WG Phase 1 report proposed two flight elements, a Lander Composite and an Orbiter Composite. Launched separately to Mars, they would work together to return at least one Mars sample container to Earth. This architecture included significant ground elements: operations centres, at least one sample receiving facility, and at least one curation facility.

In the Phase 1 concept (Figure 2-1), the Lander Composite – including a surface rover and a Mars Ascent Vehicle (MAV) – would perform a direct entry and a soft landing on the surface of Mars. The rover would drive away from the Lander platform to acquire surface samples, including rock cores, and then return to the Lander platform. The platform would be equipped with mechanisms to load samples into a container on the MAV. The platform also would have the capability to acquire samples in case of rover failure. All equipment in contact with Mars samples would have to be sterile in order to avoid false positive results when analysed on Earth. The MAV would launch the sample container into low-Mars orbit for retrieval by the Orbiter Composite.

The Orbiter Composite would include propulsion, a rendezvous and capture system, and an Earth Return Vehicle (ERV). At Earth, the ERV would release an Earth Entry Vehicle (EEV)—much like those employed on the NASA Stardust and Genesis sample return missions. Once the EEV landed, the ERV would then divert away from Earth on a non-return trajectory.

The ground segment for this architecture would consist of mission and control centres for both flight composites, a set of telecommunication ground stations, and sample return and curation facilities. Sample return facilities (SRFs) would provide containment for flight hardware and samples returned from Mars to meet planetary protection requirements. The SRF's primary function would be to protect the Earth from back contamination while necessary test protocols were conducted to determine if the samples were safe for release.

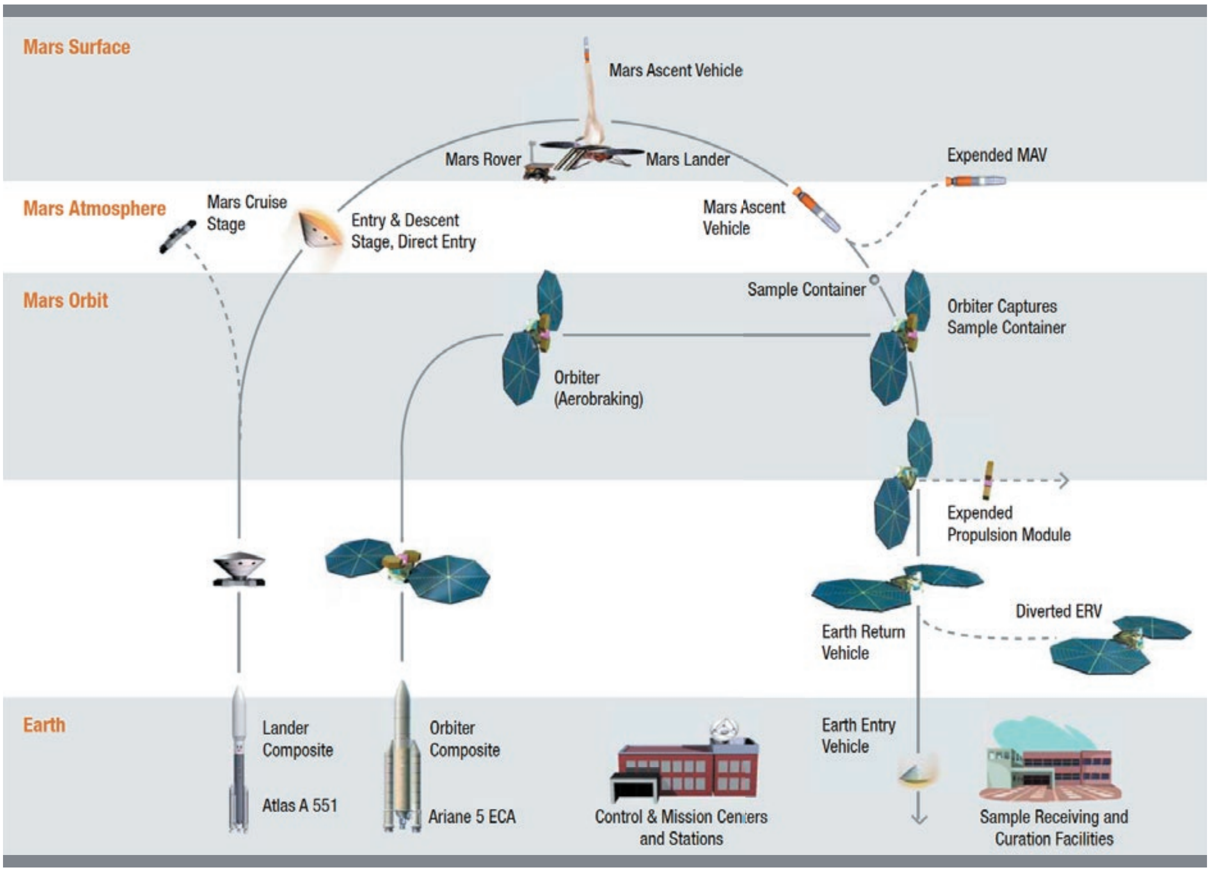


FIGURE 2-1: iMARS WG Phase 1 reference architecture.

Challenges posed by this architecture included:

- Mass incompatibility of the first element with available launch capabilities,
- Programmatic weakness in schedule management and failure mitigation plans, and
- High cost of the first element.

These issues have been addressed in the updated architecture presented in this report.

2.2 Advances Since 2008

Since 2008, numerous exploration missions to the Mars system[1], other planetary exploration missions to the Moon and asteroids, and space astronomy missions have yielded scientific insights and technology demonstrations that are useful to planning an MSR campaign.

Phoenix Mars Lander (USA, May 2008 landing), Phobos-Grunt (Russia, China) (Nov 2011 launch), Mars Science Laboratory (MSL) (USA, Nov 2011 launch), MAVEN Orbiter mission (USA, Nov 2013 launch), and Mars Orbiter Mission (India, Nov 2013 launch)[1]

Technology	Mission	Applicability to MSR
Guided entry into Mars atmosphere	Mars Science Laboratory (NASA)	The spacecraft's descent into the martian atmosphere was guided by small rockets on its way to the surface, controlling the spacecraft's descent until the rover separated from its final delivery system, the sky crane. This landing technique allows landing larger and more capable rovers carrying more science instruments.
Sky crane terminal descent	Mars Science Laboratory (NASA)	With spacecraft velocity close to zero, the sky crane lowered the rover to the surface from the descent stage. At touchdown, the descent stage separated from the lander and flew away, allowing the landed system to begin its mission
Multi-Mission Radio-isotope Thermoeleic Generator (MMRTG) for rovers	Mars Science Laboratory (NASA)	MMRTGs are a new generation of long-lived, reliable nuclear power systems ideally suited for missions involving autonomous operations in the extreme environments of space and on planetary surfaces. They reliably convert heat into electricity, generate power in increments (100+ Watt), optimize lifetime power levels (14+ years), minimize weight and ensure a high degree of safety.
Drilling	Mars Science Laboratory (NASA)	MSL's Powder Acquisition Drill System can acquire powdered rock samples from up to 5 cm inside the surface of a rock. This system is part of the Sample Acquisition, Processing and Handling subsystem.
	Rosetta/Philae (ESA)	Philae's Sample Drill and Distribution system includes an integrated drill, sampler tool, and a carousel designed to collect soil samples at depths of up to 230 mm.
Asteroid sample return (EEV)	Hayabusa (Japan)	Hayabusa performed "touch-and-go" landing on asteroid Itokawa and return samples.
Rendezvous with small body	Rosetta (ESA)	The Rosetta mission soft-landed its Philae probe on comet 67P/Churyumov-Gerasimenko – the first comet landing in history.
	Hayabusa (JAXA)	Hayabusa performed "touch-and-go" landing on asteroid Itokawa

TABLE 2-1: Technologies applicable to MSR.

These missions have advanced our understanding of our Solar System and the Universe and also have matured critical technologies applicable to MSR. Table 2-1 provides an overview of these technologies. The iMARS WG Phase 2 has also considered the results of multiple studies and related technology developments that have significantly increased understanding of how to execute an MSR campaign.

Priority	Objective Reference #	Objective Description
1	A1	Critically Assess any evidence for past life or its chemical precursors, and place detailed constraints on the past hability and the potential fr preservation of the signs of life
2	C1	Quantitatively constrain the age, context and process of accretion, early differentation and magmatic and magnetic history of Mars,
3	B1	Reconstruct the history of surface and near-surface process involving water.
4	B2	Constrain the magnitude, naturem timing, and origin of past planet-wide climate change.
5	D1	Assess potential environmental hazards of future human exploration.
6	B3	Assess the history and significance of surface modifying process, including, but not limited to: impact, photochemical, volcanic, and aeolian.
7	C2	Constrain the origin and evolution of the martian atmosphere, accounting for its elemental and isotopic composition with all inert species.
8	D2	Evaluate potential critical resources for future human explorers.
Additional	A2	Determine if the surface and near-surface materials contain evidence of extant life.

TABLE 2-2: MSR science objectives as defined in McLennan et al. (2011).

Figure 2-2, reproduced here from McLennan et al. (2011), illustrates how prioritised scientific objectives guide MSR architecture, demonstrating how science drives engineering requirements.

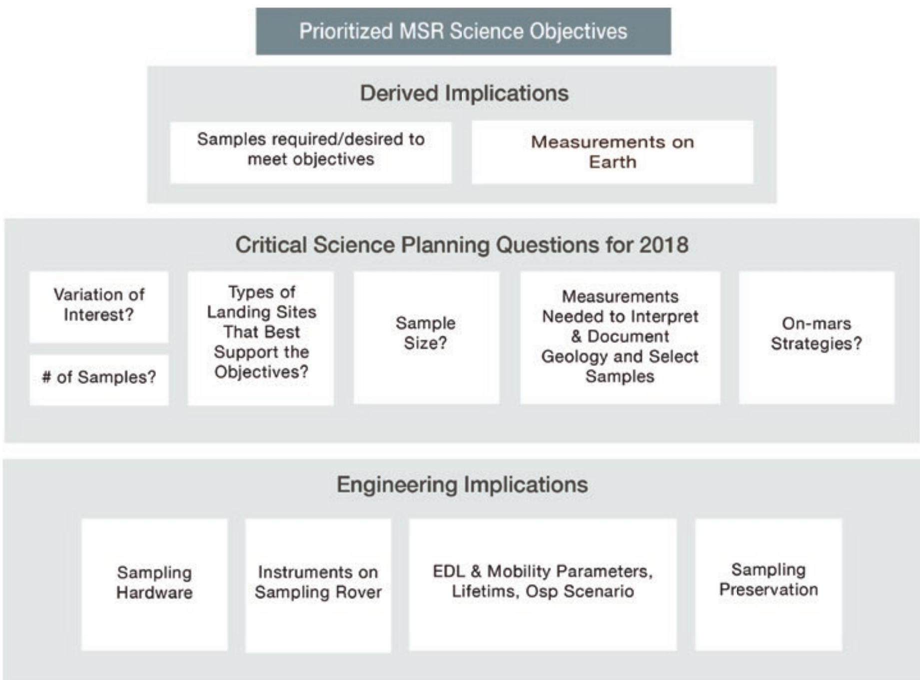


FIGURE 2-2: Science objectives and engineering implications (McLennan et al., 2011 – Note: This report assumed a 2018 launch date for a sample caching rover; hence, the date indicated in the figure).

2.3 Science Objectives and Engineering Implications

As outlined in the E2E-iSAG report (McLennan et al., 2011), top-level science objectives for MSR are presented in Table 2-3. Figure 2-2, reproduced here from McLennan et al. (2011), illustrates how prioritised scientific objectives guide MSR architecture, demonstrating how science drives engineering requirements. These high-level scientific objectives require sampling from multiple regions of interest (ROIs) on the surface of Mars and thus landing in proximity to an ROI. Scientific objectives drive specific requirements for mobility, sampling and storage. Three different types of samples would be needed to fulfil these scientific objectives (McLennan et al., 2011, Table 6): rock, regolith, and atmospheric.

Top-Level Scientific Aim	Candidate sample attributes
A. Life	Any rocks/material preserving primary textures and sedimentary structures, in order to map different layered deposits.
B. Surface	Different samples isolated from each other, fresh samples below recent rinds, preservation of stratigraphic orientation for each sample. Visit Noachian/Hesperian region of interest.
C. Planetary Evolution	Igneous texture and distribution of elements (spatial resolution), orientation to Martian surface (paleomagnetic samples) and isolation from magnetic fields. Visit Noachian and early Hesperian igneous outcrop. Atmospheric samples.
D. Human Exploration	Airfall dust (biohazard, hazard to equipment), surface soil, shallow subsurface soil, regolith

TABLE 2-3: E2E-iSAG scientific aims, as outlined in McLennan et al. (2011).

Engineering implications of these desired sample types are:

1. Landing site, landing ellipse, rover mobility and lifetime: Assuming the candidate landing sites identified in the E2E-iSAG report, finding relatively unaltered igneous rocks requires rover mobility and sufficient operational lifetime to reach regions of interest outside of the landing ellipse. Reducing the landing ellipse could reduce traverse distances and mission lifetime requirements.

2. In-situ measurement: The sample-collecting rover must be capable of observing and measuring the kinds of geologic features (and variations therein) that would enable investigators to choose appropriate sampling targets.

3. Regolith samples: Regolith samples should be collected from the top five centimetres of the surface, at a distance far enough from the lander to avoid any physical contamination by the landing event. Airfall dust should be collected separately from regolith samples.

4. Subsurface access: Subsurface sampling would be scientifically valuable due to the possibility of enhanced preservation of organics.

5. Replacement of collected samples: The scientific value of sample collection would be significantly enhanced if the sampling rover were capable of replacing at least 25 percent of samples collected earlier with samples of higher value collected later.

6. Sample storage and lifetime: Storing samples on Mars, perhaps for many years, and transporting them to Earth will require sample containers to be sealed. Individual sample tubes must be sealed, and the sample return canister must be sealed before leaving Mars to avoid a significant pressure differential across sample tube seals during transit.

7. Sample preservation: Samples delivered to Earth must retain the physical and chemical characteristics they had at the time of collection. Samples must preserve igneous texture and distribution of elements (spatial resolution), orientation to the martian surface (paleomagnetic samples), isolation from magnetic fields (isolate samples from each other), and stratigraphic orientation. Samples must be returned free of contamination.

8. Number of samples, sample size, and total mass: To achieve the proposed science objectives, 30-35 samples are desired. The target mass of an individual samples is about 15 g. The total mass of returned samples should be at least 500 g.

9. Atmospheric samples: The objective is to collect at least one atmospheric sample of 50 cm^3 at Mars ambient atmospheric conditions. If two atmospheric samples are taken, one should be collected at the atmospheric pressure minimum and the other at the pressure maximum. Atmospheric temperature and pressure should be measured at the time of sampling. The gas container should maintain a gas-tight (ultra-high-vacuum quality) seal.

2.4 Top-Level Campaign Requirements

In translating science requirements to design specifications, the iMARS WG Phase 1 report outlined minimum top-level MRS Campaign Requirements (CRs), which apply to campaign elements but are independent of architectural implementation. They are:

CR-1 MSR shall collect samples of rock, granular materials (regolith, dust) from various regions of scientific interest, and atmospheric gas.

A sample-collecting rover shall be able to travel sufficient distance to reach each region of scientific interest and including a sample collection system capable of collecting multiple samples in diverse material.

CR-2 MSR shall collect in-situ information for sample selection and establishment of its geological context.

The sample collection element of the MSR campaign shall include multiple instruments, including at least microscopic imager, to conduct the elemental chemistry and mineralogy analyses required to select samples of interest.

CR-3 MSR shall return to Earth a minimum of 500 g sample mass.

This is the recommendation of MEPAG ND-SAG (2008) based on analysis of meteoritic sample investigations and reaffirmed by the E2E-iSAG (McLennan et al., 2011).

CR-4 MSR shall maintain the scientific integrity of samples from collection on Mars through containment on Earth.

MSR systems in contact with samples shall be designed to meet science requirements for sample preservation (e.g., temperature range, radiation levels, shocks, pressure) as well as integrity and cleanliness. MSR shall also preserve sample properties over extended storage durations, by hermetic sealing of samples.

CR-5 All MSR flight and ground elements shall meet planetary protection requirements for Category V, restricted Earth return, established by COSPAR (see Appendix 6.2).

This requirement originates from COSPAR planetary protection policy (Kminek and Rummel, 2015). COSPAR policy is the baseline for applicable NASA and ESA planetary protection requirements (NPR 8020.12D, 2011; ESSB-ST-U-001). Policy and requirements will be updated in response to expert recommendations, for example, from:

- The European Science Foundation (Ammann et al., 2012): the probability that a single unsterilized particle of 0.01 micron (previous standard, 0.2 micron) is released in the terrestrial biosphere shall be less than $1x10^{-6}$; and
- The U.S. National Research Council (NRC, 2009). NASA and ESA planetary protection advisory groups have endorsed the NRC's latest recommendations, and ESA is already applying them in developing MSR technologies.

The sience definition team to be established for the MSR campaign will elaborate the details of sample collection, location and characterisation for CR-1 and CR-2 and preservation of sample integrity as per CR-4.

2.5 Mars Sample Science and Planetary Protection Considerations

2.5.1 Probability of Extant Life in Returned Samples

Extant life detection is not among top science priorities described by E2E-iSAG (McLennan et al., 2011), and the MSR campaign will not be optimized for life detection. However, returned samples will undergo a battery of life detection tests to meet planetary protection requirements. Thus, planetary protection measurements can be considered a necessary but largely insufficient use of Mars samples.

E2E-iSAG determined that the geological context for possible extant life on Mars was insufficiently understood to plan a sample return mission focused on extant life detection. However, the likely geological context for possible fossil life on Mars is much better understood from terrestrial experience and Mars exploration to date (e.g., Grotzinger et al., 2014). E2E-iSAG thus recommended that a sample return campaign should focus on the search for fossil evidence of ancient life and its prebiotic precursors.

Nonetheless, returned samples must be treated as if they might contain extant life in order to protect terrestrial life from any possibility of contamination by extraterrestrial life. Should planetary protection protocols applied to samples generate a positive detection, a new task committee should be formed immediately to revisit and revise sample management recommendations made in this report.

The sample management plan described in this report provides new guidelines for scientific use of samples to meet primary goals for MSR, consistent with meeting planetary protection requirements.

2.5.2 Avoiding the "Stuck in Containment" Scenario

A returned-sample management plan will need to assess the timeline within which samples can be made available to the wider scientific community. Previous studies have recommended that samples be released as soon as it is safe to do so to minimise the potential of a "stuck in containment" scenario whereby external scientists would be restricted or even prohibited from accessing samples for investigation (iMARS WG, 2008).

Scientists now recognise that sample analyses required to meet planetary protection requirements are more or less the same ones they would want to perform in the interest of scientific investigation (Allwood et al., 2013; Kminek et al., 2014). Thus, the scientific benefits of planetary protection measurements are immense (e.g., Summons et al., 2014). Consequently, the recommended sample management plan encourages providing external scientists access to samples while still in containment.

As measurements are made to meet planetary protection requirements, the likelihood of finding extant life and the likelihood of destroying extant life by sterilisation of samples diminish in lock step. While possible risks to safety and science must be balanced, those risks decrease greatly with each subsequent negative result. Thus, it is possible that upon completion of some set of minimum planetary protection measurements, external scientists' access to samples could be expedited.

One way to expedite access could be to have a "rolling release", by which samples deemed safe (by testing or sterilisation) are released while more problematic samples might be held in containment for a longer period. Planetary protection protocols, a timeline for release of samples, and criteria to be used for sample release should be developed and agreed to by peer review and appropriate advisory committees and published well ahead of sample return. If samples are not released when criteria are met or sample managers decide to change the criteria, an external peer review should be triggered. Finally, a mechanism for decision-making regarding sample release, with authorities and responsibilities clearly defined, should also be in place ahead of time.

2.5.3 The Need for a Planetary Protection Protocol

Distinguishing between scientific and planetary protection elements of returned-sample analysis depends on establishing a clear decision-making framework for sample release that meets national and international planetary protection standards. The hypothesis-based approach outlined by Allwood et al., (2013; Kminek et al., 2014) would likely have to run in parallel with sample investigation. This approach should be the basis for developing science and planetary protection protocols.

In developing these protocols, several open questions remain:

- Exactly which measurements will be required to fulfil planetary protection requirements?
- What instrumentation will be required to make these measurements?
- Will the probability of finding extant life in Mars samples ever be determined to be low enough to warrant release of unsterilized samples from containment?
- What fraction of a sample should be designated for planetary protection measurements, and will this value change as samples are interrogated?
- To what degree must this fraction be "representative"?
- At what stage will planetary protection measurements be deemed sufficient to accept the risk of losing any possible evidence of life through sterilization?

Answering these questions will be central to the design and management of the SRF, especially for operations beyond the initial period of preliminary examination. Answers will need to be well understood before any sample management plan can be finalized. While noting that previous reports have developed initial iterations of a planetary protection protocol (Rummel et al., 2002; Ammann et al., 2012; Kminek et al., 2014), the iMARS WG strongly recommends that a task group be convened as soon as possible to draft a formal planetary protection protocol for returned martian samples.

> *Finding: An accepted Planetary Protection Protocol for returned martian samples should be produced by an internationally appointed working group as soon as is feasible.*

2.6 Applicability of Previous Planetary Sample Return Missions

2.6.1 Sample Management

MSR will not be the first instance of dealing with extraterrestrial samples on Earth. The following sample return missions (past, present, future) will help to shape planning for Mars sample management:

- Genesis: return of solar wind samples in 2004,
- Stardust: return of cometary material in 2006,
- Hayabusa 1: return of an asteroid sample in 2010,
- Phobos-Grunt: return of a sample of Phobos, failed at launch in 2011,
- Hayabusa 2: launched 2014, will return a sample of asteroid Ryugu, and
- OSIRIS-REx: launched in 2016, will return at least 60 g of material from asteroid Bennu.

Thus the planetary science community already has considerable experience working with samples from throughout the solar system (including martian and other rare meteorites collected on Earth). Among important "lessons learnt" from past experience with extraterrestrial samples (Allton et al., 1998; Mangus and Larson, 2004; Allen et al., 2011) are the needs to:

- Incorporate sample handling and management planning into mission design;
- Define roles and responsibilities that encourage good relations among scientists, quarantine officials and curators; and
- Operate according to the principle that the highest quality samples should be studied by the highest quality laboratories.

While previous sample return missions can help inform planning for an MSR campaign, samples returned from Mars will present unique challenges for preliminary examination, access, allocation, data rights and curation (e.g., Allton et al., 1998; Neal, 2000; Beaty et al., 2009) that must be thoroughly addressed well ahead of receiving samples on Earth. Table 2-4 summarises issues relevant to Mars sample analysis and distribution and relevant experience with previous sample return missions. Table 2-6 lists aspects of international deep ocean drilling programs (http://www.iodp.org) that may be relevant to MSR (see Section 2.7).

Unlike extraterrestrial samples returned to Earth thus far, Mars samples will require extended periods under biological containment to ensure that no danger is posed to human health or the environment by the unintended release of harmful organisms. The SRF will provide containment as least as restrictive as Biosafety Level (BSL) 4 (U.S. Department of Health and Human Services, 2009; see Appendix A.3), requiring a

TABLE 2-4: MSR science objectives as defined in McLennan et al. (2011).

Mission/Samples	Storage / Quarantine / Curation (incl. Planetary Protection)	Preliminary Examination	Sample Return Facility Instrumentation	Technical Support	References
Mars Sample Return	BSL-4/Class 10 for up to ~20 years for unsterilized samples; TBD (but likely Class 10-100) for sterilized and otherwise released samples	Extensive, within SRF; requires analyses necessary to meet PP protocols; scope of other analyses TBD	Extensive cutting-edge instrumentation for PP analyses; TBD for other analyses; requires Class 10, 100 and 1000 analytical laboratories	Extensive technical support for PP analyses, preliminary examination, visiting scientists' analyses and curation	Neal, 2000; Committee on Planetary and Lunar Exploration, 2002; MEPAG ND-SAG, 2008; Beaty et al., 2009; McLennan et al., 2012; this study
Apollo Lunar Samples (JSC: CAPTEM)	50-day post-return quarantine; quarantine requirements ended with Apollo 14; pristine samples permanently stored in Class 1,000 conditions	At Lunar Receiving Lab (LRL) during missions with quarantine periods; at LRL and off-site for later missions	Instrumentation for basic sample characterization (e.g., petrography, bulk composition	Long-term technical support for curation; extensive but short-term support for preliminary examination	LSPET, 1973; Taylor, 1994; Allton et al., 1998; Mangus & Larsen, 2004; Allen et al., 2011
Antarctic Meteorites (JSC; Smithsonian; MWG/MSG)	No quarantine or PP measurements; storage in better than Class 1,000 conditions; rare samples stored in N2 cabinets	Limited to basic description and classification	Basic facilities for characterization; in rare cases O-isotopes and electron probe analyses obtained offsite for classification	Long-term technical support for curation; otherwise limited to making specialized thin sections	Walzenbach et al., 2006; Allen et al., 2011
Aircraft Cosmic Dust, Genesis Solar Wind; Stardust Comet; Stardust Interstellar Dust; Hayabusa Asteroid (JSC: CAPTEM)	No quarantine or PP measurements; samples permanently stored in Class 10-100 conditions; subsets of Genesis and Stardust samples stored offsite; Hayabusa samples represent small subset of main (JAXA) collection	Cosmic Dust: selected samples examined by SEM-EDS Stardust Comet: extensive nine month preliminary examination mostly offsite Stardust Dust: extensive preliminary examination (mostly offsite)	Basic ongoing characterization – SEM, FTIR, optical microscopy	Long-term technical support for curation; limited technical support for ongoing characterization	Zolensky et al., 2008; Allen et al., 2011; Westphal et al., 2014
Hyabusa Asteroid Samples (JAXA	No quarantine or PP measurements; samples maintained and handled in Class 100-1,000 conditions; subset of samples held by JSC	X-ray tomography of sample containers; FE-SEM-EDS analysis; most other preliminary analyses offsite	Sample identification and manipulation facilities; field emission SEM-EDS in Class 1,000 clean room	Technical support for curation; limited support for preliminary examination	Yada et al., 2014
Deep Sea Drilling Samples (DSDP, IODP)	Moratorium on distribution of samples until one year after cruise ends; cores permanently stored in ambient conditions at multiple sites	Extensive preliminary examination during cruise aboard drilling ship and during moratorium period at land-based labs	Extensive onboard instrumentation, ranging from cutting-edge analyses to routine sample characterization	Technical support for preliminary examination, ship scientists' research analyses and long-term curation	Smith et al., 2010; IODP, 2001, 2012

Technology	Technology	Applicability to MSR	Delta developments required for MSR
Earth entry and landing	Sample-capsule Thermal Protection System (TPS) and capsule recovery operations demonstrated with Stardust, Genesis, and Hayabusa 1.	TPS material is applicable for the MSR Earth Entry Vehicle (EEV). EEV recovery operations would be similar for MSR	Hard landing is likely to be required for MSR since current parachute technology is not reliable enough to meet planetary protection requirements (note: crushable structure developments are ongoing for Phobos SR).
Rendezvous in Mars orbit	Hayabusa 1 performed a rendezvous with an asteroid. Hayabusa 2 and OSIRIS-REx plan rendezvouses.	Autonomous GNC for terminal descent phase could be used for MSR rendez-vous. Sensor suite (lidar; camera for Hayabusa 1 &2, OSIRIS-REx) for relative navigation to the target could be applicable. Operational concept could be be similar	Rendezvous with the orbiting Mars sample will require capabilities beyond current developments: detection of a very small object at far range, accurate spacecraft guidance & control at capture, known features of the sample container that can be used for relative navigation.
Sample handling and sealing	Partial success of Hayabusa 1 for sample acquisition & transfer to EEV. Hayabusa 1 & 2, OSIRIS-REx all feature sample acquisition, transfer to EEV and sealing.	Techniques and operational concept for sample acquisi-tion and transfer to the EEV can have partial applicability to MSR. Sample container sealing technique can be applicable for preserving sample integrity.	MSR will require more sophisticated acquisition techniques. Bio-sealing and seal monitoring require specific techniques and redundant approaches to reach reliability require-ments. Specific techniques need to be developed for "breaking the chain with Mars."

TABLE 2-5: Technologies developed for other sample return missions that could be applicable to MSR.

substantial technical support staff. The duration of sample containment will likely be months to decades. For comparison lunar samples were quarantined for only 50 days, and quarantine was only applied for Apollo 11, 12 and 14 (Mangus and Larson, 2004).

Moreover, the MSR campaign will require a long-term program of cutting-edge preliminary examination, including evaluation for biology and other potential hazards. The BSL-4 SRF facility will need to contain extensive instrumentation to enable the conduct of measurements required for planetary protection and preliminary characterization (Beaty et al., 2009).

In contrast, current extraterrestrial-sample return and curation facilities (NASA/JSC, JAXA) have limited analytical capabilities. Existing facilities have not had to deal with BSL-4 containment and only rarely with ultraclean analytical laboratories of the level required for Mars samples (Beaty et al., 2009).

2.6.2 Technology

Although previous and planned sample return missions have advanced the development of MSR-related technologies, additional investments in key areas will be required to enable MSR. Table 2-5 summarises technologies demonstrated on sample-return missions and further developments needed for application to MSR.

2.7 International Ocean Discovery Program as an Analogue to MSR

In researching possible operational and sample-management scenarios to incorporate into planning for MSR, the iMARS WG found the International Ocean Discovery Program (IODP) to be a particularly useful model. Under various guises[2], this program has been operating for nearly five decades, mounting over 340 expeditions (or "legs") and extracting many thousands of metres of precious sediment and rock cores from the ocean floor.

The IODP is a useful model for MSR management in its scope, international participation, and management structure. Roughly 25 countries contribute to its annual budget (U.S.$170M in 2012), which funds a range of multinational activities (IODP, 2001; Smith et al., 2010; National Research Council, 2011), such as:

- Retrieving drill cores from the deep ocean bottom,
- Performing extensive onboard preliminary examination of collected samples,
- Identifying site-specific scientific experts and developing site-specific sampling strategies for each expedition,
- Establishing post-cruise moratorium periods during which preliminary data and sample access are limited to expedition scientists,
- Using well-defined and well-tested mechanisms for sample allocation and distribution and data access, and
- Following long-term curatorial procedures for sedimentary and igneous core samples.

Table 2-6 summarizes some of the ways in which the IODP's experience has informed the iMARS WG's Phase 2 analysis.

The iMARS WG strongly recommends that the IODP be consulted during the development of Mars sample science operation procedures and sample management planning.

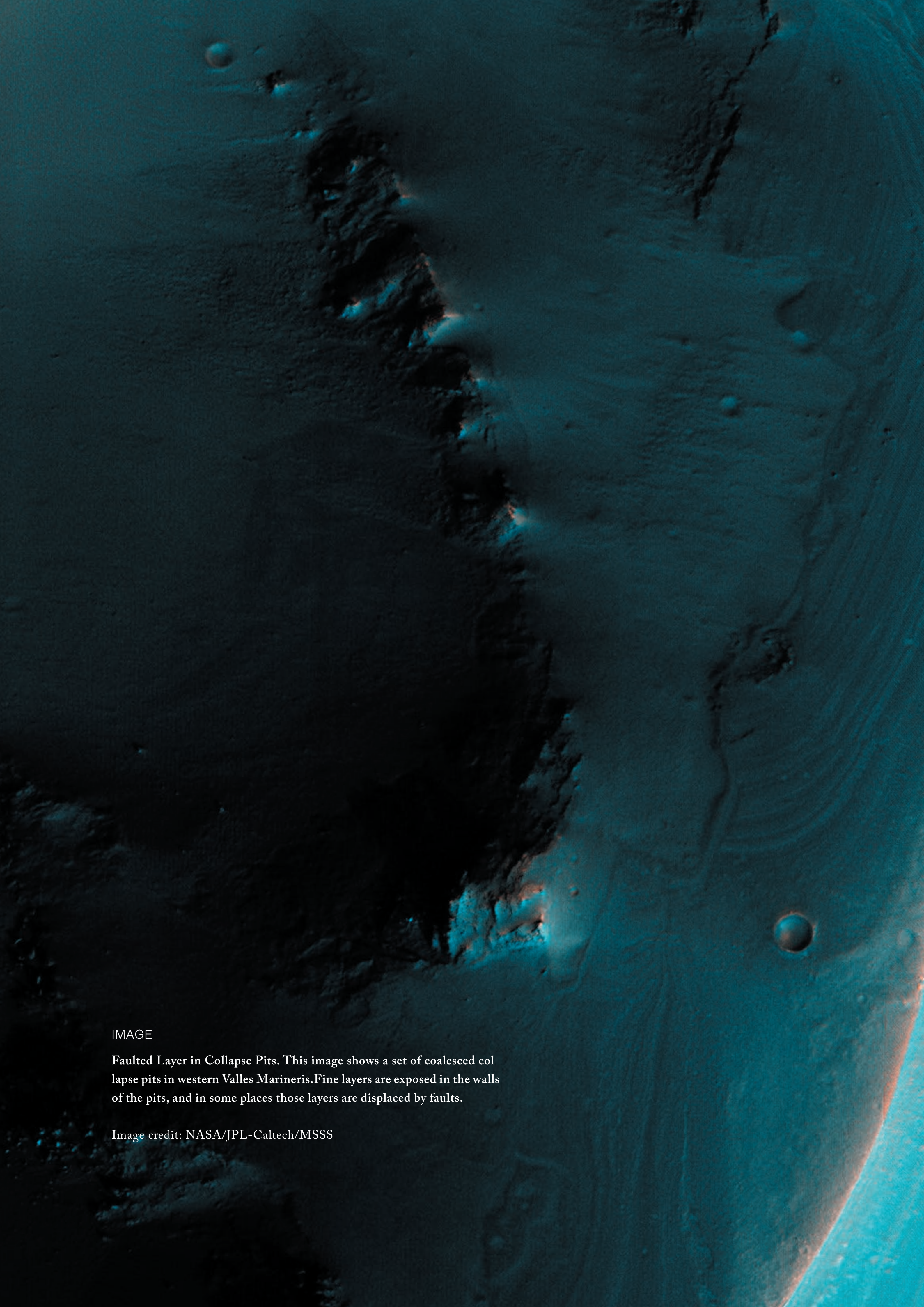
Deep Sea Drilling Project (DSDP), 1968-1985; Ocean Drilling Program (ODP), 1985-2004; Integrated Ocean Drilling Program (IODP), 2004-2013; International Ocean Discovery Program (IODP), from 2014.[2]

Finding: The IODP should be consulted in developing sample science operation procedures and sample management planning for MSR.

TABLE 2-6: Areas where experience with international deep-sea drilling programs may be useful for designing and implementing an MSR sample management strategy.

International Deep-Sea Drilling Experience	Relevance to Mars Sample Management
ORGANIZATION AND SCIENCE ADVISORY STRUCTURE: An independent management corporation with strong science advisory structure.	Provides model for interface between management involving international partners and sample science community.
INTERNATIONAL PARTICIPATION: 25 nations with well-defined roles/responsibilities and sample/data rights.	Provides model framework for international participation in MSR, including how to evaluate "contributions".
SAMPLING STRATEGIES: For each expedition, "leg-specific sampling strategies" are tuned to science questions being addressed and sample types being recovered (sediment, igneous, paleo-climate).	Provides model for "suite-specific sampling strategies" recommended in this report.
MORATORIUM PERIOD: Each expedition has a moratorium period lasting one year after the end of cruise, in which only shipboard scientists (and shore based collaborators) have access to samples and data.	Provides example of dealing with restrictive sample access during preliminary examination phase of Mars samples and during sample containment in general.
EXTERNAL SCIENTISTS: Each expedition is staffed by temporary expert scientists (including lead scientists) who work with extensive permanent technical staff and a small permanent science staff.	Provides model for coordinating external expertise for MSR, personnel aspects for the SRF (e.g., guest scientist programs) and preliminary examination teams.
PRELIMINARY EXAMINATION: Protocol-driven preliminary examination includes standard measurements on all cores and site-specific measurements (derived from sampling strategies).	Provides guidance on designing preliminary examination protocols for samples from different suites.
ANALYTICAL FACILITIES: Drilling ships operate extensive, sophisticated analytical facilities during cruise for preliminary examination and onboard research, staffed by permanent technical and science staff.	Provides model for staffing and operating extensive analytical facilities at SRF, including preliminary examination and planetary protection analyses.

International Deep-Sea Drilling Experience	Relevance to Mars Sample Management
SAMPLE DISTRIBUTION: Well-established procedures involve sample allocation committees and an oversight advisory board for appeals and special requests.	Provides basis for designing the sample allocation boards proposed in this report.
NATURE OF SAMPLES/CURATION: Samples are "geological", retrieved as cores and sub-sampled/distributed in accord with geological context (bedding, fragmental, texture); long-term sample curation (>50 yrs) at multiple localities; Curatorial Advisory Board; reserve of about 50% of drill core for future research.	Mars samples will be more than one order of magnitude smaller, but otherwise will bear many similarities to ocean core samples; provides example of long-term curation of precious samples that are very highly sought for research.
DATA ARCHIVING: Extensive web-based system for posting data in accessible format with two levels of access (password protected Moratorium phase; public access post-Moratorium.	Provides model for data archiving and making data obtained from Mars samples during preliminary examination / characterization accessible to different categories of researchers.

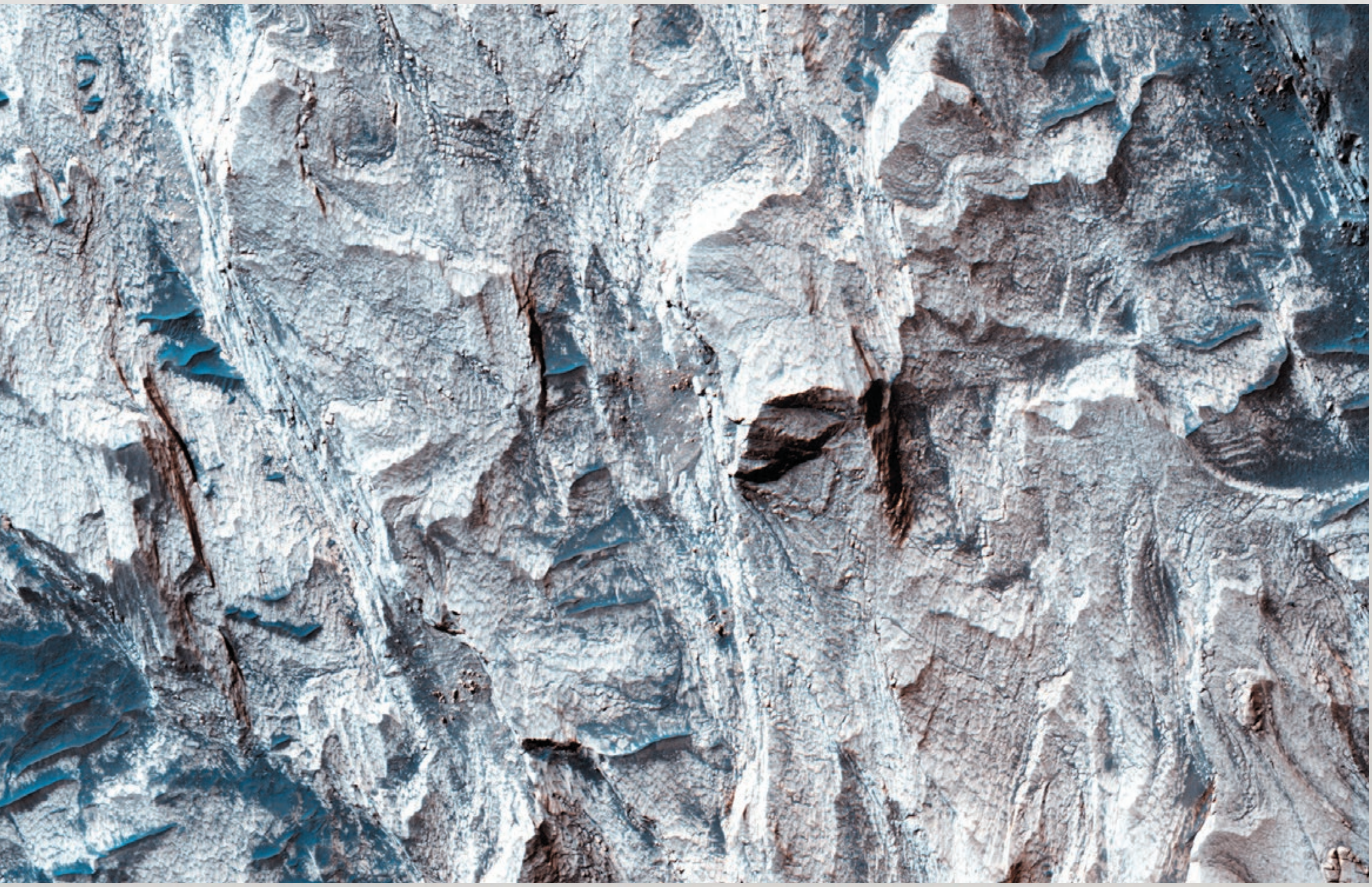


IMAGE

Faulted Layer in Collapse Pits. This image shows a set of coalesced collapse pits in western Valles Marineris.Fine layers are exposed in the walls of the pits, and in some places those layers are displaced by faults.

Image credit: NASA/JPL-Caltech/MSSS

III. MSR Campaign Architecture and Implementation



ABOVE IMAGE

Possible Sulfate Deposits in West Melas Chasma. Melas Chasma is the widest segment of Valles Marineris, the largest canyon in the Solar System.

Image credit: NASA/JPL-Caltech/Univ. of Arizona

Architecture options for MSR have evolved over time as the technical and programmatic landscape has changed and technological development has advanced. Key technical drivers of architecture evolution include a better understanding of entry, descent and landing (EDL) capabilities and constraints, longer-range rover design, advances in sample acquisition and handling, and an evolving understanding of campaign risk and robustness. Programmatic drivers of cost and schedule also affect the architecture, requiring the flexibility to respond to changes in funding and partnership.

The architecture described in this report is responsive to known technical constraints and flexible enough to respond to programmatic changes that may occur during the execution of the campaign elements. Alternative architectures are discussed and potential timelines for the campaign are presented here as well.

3.1 Implementation of Mars Sample Return

3.1.1 MSR Reference Architecture

Several potential architectures have been envisioned to execute an MSR campaign, considering technical, programmatic and policy guidelines and constraints. Figure 3-1 presents a generalized map of the essential functions for MSR, collected into a series of potential architectural approaches. Each architecture can meet the overall objectives, with different technical requirements, costs, schedules and risk postures. All architectures include one or more flight missions, augmented with the "+1" ground-based activities to perform the retrieval, quarantine and curation of the samples after return to Earth.

In the 1+1 architecture, one flight mission accomplishes the functions of selecting the samples, packaging them and returning them to Earth. The advantages of this architecture are a single launch with all essential flight elements designed and delivered at the same time. This provides efficiencies in the design and development process, where all interfaces and requirements can be developed simultaneously, ensuring an efficient technical solution, and the (relatively) short span of time between mission launch and samples returned to Earth. However, the drawbacks of this architecture include high initial cost to develop all of the capabilities at once and potentially higher risk putting all the functions on one launch (requiring a large launch vehicle).

The 2+1, 3+1 and 4+1 architectures sort essential functions into multiple flight elements that are launched independently. The advantage of performing MSR with multiple flight elements are reducing initial cost by distributing it across elements, reducing the risk of mission failure, and enabling flexibility in programmatic and policy decision making. The main drawback of multiple-element architectures is that they increase the time between initial collection of samples and their return to Earth.

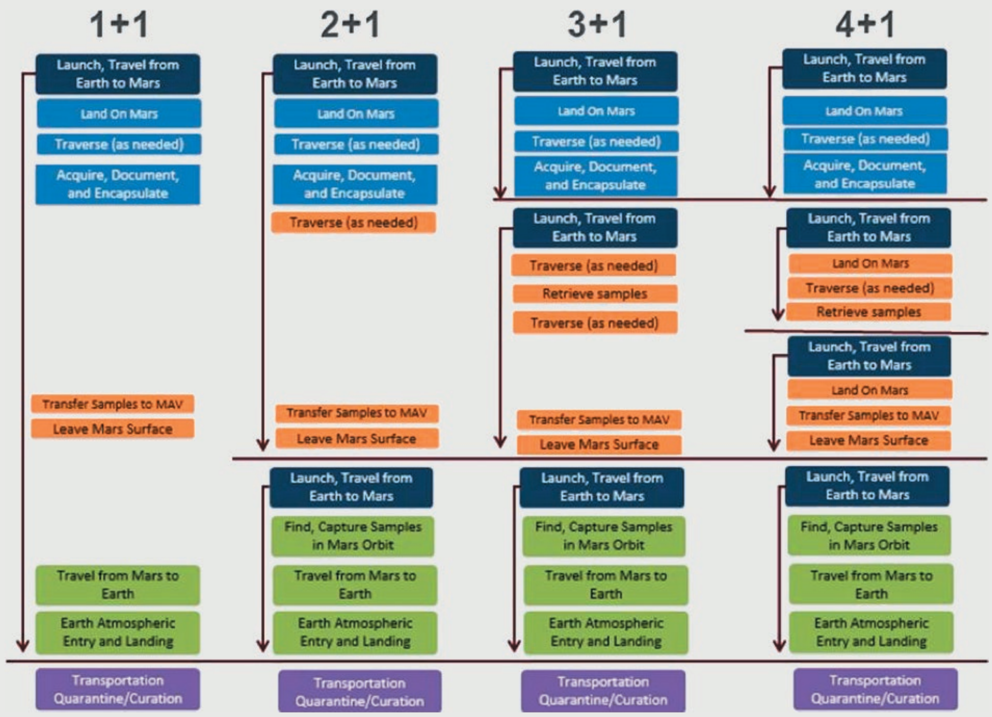


FIGURE 3-1: The essential functions of MSR can be performed in multiple MSR architectural options (Source NASA).

The iMARS WG Phase 2 team has chosen the 3+1 architecture as its reference concept, with three flight missions to Mars and an Earth-based sample-handling element. This concept differs from the one detailed in the iMARS WG Phase 1 report (iMARS, 2008) by splitting sample collection and sample retrieval/return into separate flight elements – a more robust technical approach. Figure 3-2 shows the essential functions of MSR distributed into three flight elements: a Sample Caching Rover (SCR), Sample Return Lander (SRL), and Sample Return Orbiter (SRO).

> *Finding: A "3+1" architecture, consisting of three flight missions and at least one ground-based SRF, is recommended to implement MSR.*

Technical and Programmatic Advantages of the 3+1 Architecture

A principal feature of the 3+1 architecture is the placement of samples in a stable state after the SCR and SRL mission:

- The SCR will collect samples into one or more caches, with the ability to be stored in a stable state for at least a decade, to be available for retrieval.

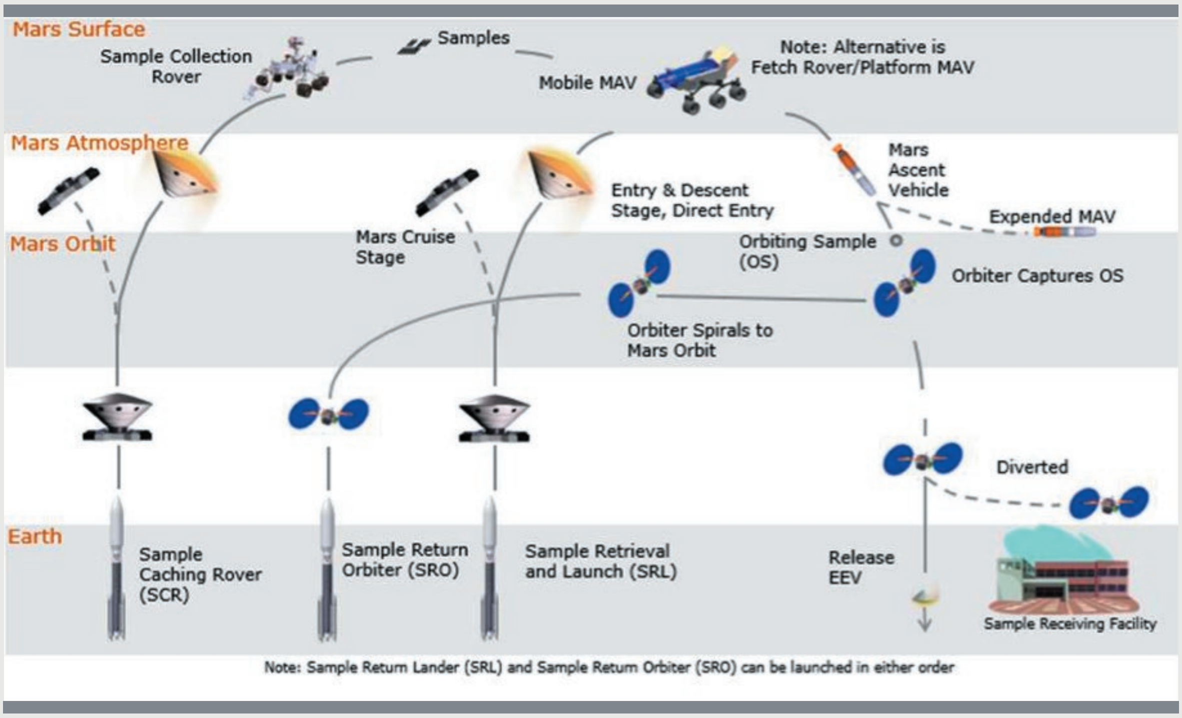


FIGURE 3-2: The 3+1 MSR Campaign architecture allocates the essential functions to three flight missions, and provides technical, programmatic and policy flexibility for the implementation (Source NASA).

- The SRL mission will place an Orbiting Sample (OS) chassis in a stable, long-term orbit of Mars, available for rendezvous and return by the SRO mission. Stable orbits of more than 50 years are achievable within currently envisioned Mars Ascent Vehicle technologies.

The 3+1 architecture and stable sample storage allow flight elements to be designed and implemented in sequence. If programmatic or technical issues delay the launch of a flight element, the change can be accommodated without degrading science return. Also, implementing sample return with multiple flight missions creates partnership opportunities to distribute activities across participating organisations, potentially mitigating programmatic and policy constraints.

Defining the 3+1 Architecture Elements

The iMARS WG Phase 2 offers the following description of the elements that make up the 3+1 architecture. Each flight element of the 3+1 architecture offers implementation options to meet requirements. The architecture described here is one possible approach to meeting requirements.

Sample Caching Rover (SCR) element: An MSL-sized rover that selects, collects, and stores rock-core and regolith samples, storing them in individual sample tubes for retrieval by the SRL.

The SCR consists of:

- An Earth-Mars cruise stage,
- Entry-descent-landing (EDL) system, and
- Mobile rover with science and sampling payload and caching capabilities.

Sample Return Lander (SRL) element: A mobile surface system that retrieves samples, a Mars Ascent Vehicle (MAV) that launches samples into Mars orbit, and an Orbiting Sample (OS) chassis that preserves samples from Mars ascent through Earth recovery. The SRL element also collects and stores atmospheric samples.

The SRL consists of:

- An Earth-Mars cruise stage,
- EDL system,
- Mobile sample retrieval system,
- Mars ascent vehicle (MAV),
- Atmospheric sampling system, and
- Orbiting Sample chassis (OS).

Sample Return Orbiter (SRO) element: A spacecraft with a rendezvous sensor suite and a mechanism for capturing the Orbiting Sample (OS) chassis in Mars orbit. The SRO element can provide telecommunications relay for surface operations and critical events. After the SRO captures it, the orbiting sample is sealed in containment and put into the Earth Entry Vehicle (EEV).

The SRO consists of:

- Earth-Mars cruise stage,
- Orbiter with a rendezvous sensor suite and a capture mechanism,
- Biocontainment system, and
- Earth Entry Vehicle (EEV).

Mars Returned Sample Handling (MRSH) element: The terrestrial infrastructure required to recover, transport, analyse, assess, curate, and distribute samples. The MRSH element consists of a sample recovery and transport system to collect the EEV and transport it to the Sample Return Facility (SRF), the primary laboratory for sample containment, assessment, analysis, and curation. With regard to the MRSH element, only details pertaining to the SRF are discussed in the remainder of this report. Recovery and transport were beyond the scope of the iMARS WG Phase 2 study.

3.1.2 Baseline Architecture Design Summary

The following sections summarise the results of recent studies, performed by iMARS WG Phase 2 participating organisations, that address the four elements of the 3+1 baseline architecture.

3.1.2.1 SCR

To meet overarching campaign objectives, the SCR mission of the MSR campaign must fulfil the following requirements:

- SCR-1 Collect rock and granular material samples to meet science requirements and avoid degradation of sample properties.
- SCR-2 Individually seal samples for transfer between the SCR and the SRL, and avoid contamination of samples per science requirements.
- SCR-3 Maintain integrity of sealed samples for an extended period of time to allow for programmatic or technical delays of SRL and SRO elements.
- SCR-4 Deposit samples in a manner that will permit retrieval by the SRL.
- SCR-5 Provide sample location context information for subsequent retrieval by the SRL.

SCR requirements can be met by an MSL-class rover with a scientific payload capable of identifying desired sampling targets, collecting contextual information, acquiring rock-core and regolith samples, and placing them into sample tubes for eventual return.

A notional SCR mission would leverage investment in MSL design, reusing elements of the mission's cruise and EDL stages and surface mobility capability. The mission also might benefit from advances in drilling technology for the ExoMars rover. This notional mission would be capable of landing in proximity to regions of interest for sampling, provide sufficient roving capability to reach at least two regions of interest, carry a scientific payload tailored to identifying potential sampling candidates and providing sample context information, and feature sample collection and caching capability.

The SCR flight element consists of a cruise stage, EDL system and surface system. The cruise stage delivers the combined EDL/lander to Mars. It provides propulsion, attitude control, telecommunications, power and thermal control for the flight elements on the cruise from Earth to Mars. During launch from Earth, the cruise stage is the primary interface between the launch vehicle and the flight system, providing data and electrical system interfaces. After separation from the launch vehicle, the cruise stage is spin-stabilized, using a star tracker for attitude determination and eight hydrazine thrusters for attitude control and propulsion. Power is provided by solar arrays and batteries, and telecommunication is via X-band through medium-gain antennas to the Deep Space Network (DSN). An essential function of the cruise stage is to provide thermal

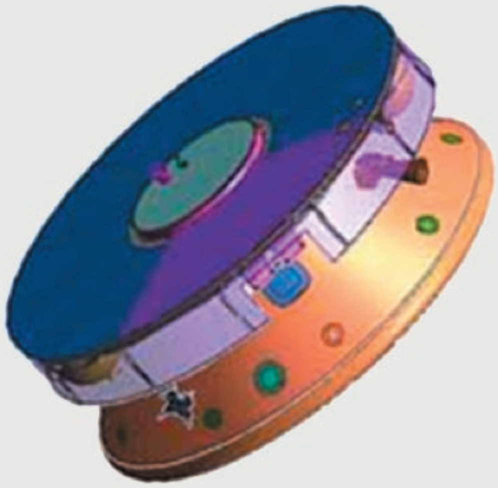


FIGURE 3-3: MSL cruise stage (Source NASA).

control for the entry system during cruise, via thermal blankets and liquid thermal control loops from the entry system to heat rejection panels. Figure 3-3 shows the cruise stage that delivered MSL to Mars in 2012.

The SCR flight element's EDL system could be based on a rebuild of the MSL EDL subsystem. Delivering the SCR through the atmosphere of Mars and depositing it on the surface requires multiple EDL stages as shown in Figure 3-4.

The first stage of the EDL system is the aeroshell, which is essential for delivering the landed system through the upper atmosphere, guiding entry and reducing velocity. Once the correct conditions are reached (triggered by velocity or by range to target), a parachute is deployed and the aeroshell is discarded. The parachute continues to reduce the velocity of the lander as it travels through the atmosphere. For the final stage of landing, the parachute is discarded and a powered descent stage is used. The powered descent stage employs thrusters to kill residual velocity toward the surface and, at a planned height above the surface, lowers the lander toward the surface on a tether. The wheels on the lander (rover) deploy on command, and when touchdown is sensed, will cut the tether. The powered descent stage will separate and fly off to avoid interfering with the rover. Operation of the EDL system is fully controlled by avionics in the rover.

The SCR rover could be based on the MSL rover, with a new scientific payload. The rover must accommodate a science payload capable of identifying, contextualising, and selecting surface samples (rock cores and

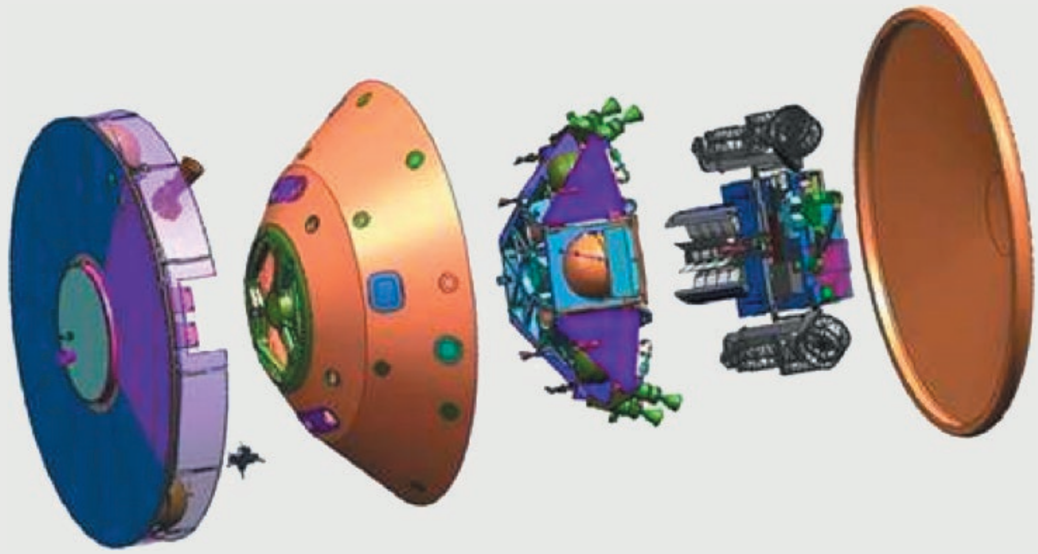


FIGURE 3-4: SCR Cruise/EDL stages with the rover element in the stowed configuration (Image courtesy NASA).

regolith) and the infrastructure required to collect the specified number of samples. Samples are packaged in individual tubes and placed in one or more caches for retrieval. The sample collection system must be able to collect samples in a manner that maintains their integrity and encapsulates them, minimizing cross-contamination.

FIGURE 3-5: An SCR could be a build-to-print copy of the MSL Curiosity rover with a new science payload and a sample collection and caching system (Source NASA).

Key Drivers and Challenges for the SCR Mission

The SCR mission is planned to meet an updated set of key MSL mission requirements. Key SCR mission drivers are to be able to access scientifically interesting landing sites up to ± 30 degrees latitude (due to communications constraints) and access multiple regions of interest at the chosen landing site. These regions of interest are independent of landing ellipse constraints and may fall outside an acceptable landing area. To accomplish these tasks, SCR mission challenges are:

- Entry, Descent and Landing: Sufficient capability to deliver a rover to a landing site with enough accuracy and mass capability to access regions of interest and collect required samples.

- Traverse Capability: Ability to traverse from landing site to regions of interest.

- Sample Collection and Handling: Ability to take multiple samples of materials with varying properties while maintaining the scientific integrity of samples, and to prepare and place samples on the surface of Mars in a manner sufficient to maintain their scientific viability for an extended period.

M2020 as a Sample Caching Rover Mission

At the present time, NASA is implementing the Mars 2020 mission (M2020) – a rover based on MSL architecture, whose mission objectives include the ability to scientifically select and collect a returnable set of samples. M2020 could meet key objectives defined for the SCR, thus fulfilling this portion of an MSR campaign. While M2020 could be considered the first step in Mars sample return, an additional SCR mission may be necessary to meet all of the SCR mission objectives detailed in this report – for instance, if drilling deeper than a few centimetres is desired.

3.1.2.2 SRL

The SRL mission is the second flight element of the MSR campaign. This mission retrieves and collects samples and injects them into a stable Mars orbit. To meet MSR campaign objectives, the SRL mission must meet the following requirements:

- SRL-1: Collect an acceptable atmospheric sample.

- SRL-2: Retrieve samples from one or more locations on the surface of Mars.

- SRL-3: Encapsulate surface and atmospheric samples in an Orbiting Sample (OS) chassis for transfer between the SRL and SRO.

- SRL-4: Enable the OS chassis to be detectable in Mars orbit.

- SRL-5: Launch the OS chassis into a long-term stable orbit around Mars.

To meet MSR campaign success criteria, the SRL mission must land on Mars in proximity to samples (within mobility constraints), find and retrieve surface samples, collect an atmospheric sample, place samples in the OS chassis and the chassis into the MAV, preserve the integrity of samples, and place the OS chassis in a stable, long-lived low Mars orbit (400-500 km) subject to sample integrity requirements.

The 2010 U.S. Planetary Science Decadal Survey (Committee on the Planetary Science Decadal Survey, 2010) described an SRL mission architecture that included a fixed landed platform with a Mars Ascent Vehicle (MAV) and a small fetch rover to retrieve the samples. The lander system would be designed to make use of MSL cruise and EDL stages and work within physical and performance constraints of the legacy systems (Figure 3-6).

The notional fetch rover would be a small, solar-powered vehicle on the order of a MER-class rover, designed for a mission duration of 180 sols (martian days) and a traverse capability of 12 km. This rover would retrieve samples placed on the surface of Mars, employing a simplified sample retrieval arm and end effector. A manipulator on the landed platform would retrieve samples from the rover, prepare them for placement in the OS chassis, and place the loaded chassis in the MAV. Figure 3-7 shows a possible design of the fetch rover and sample retrieval arm.

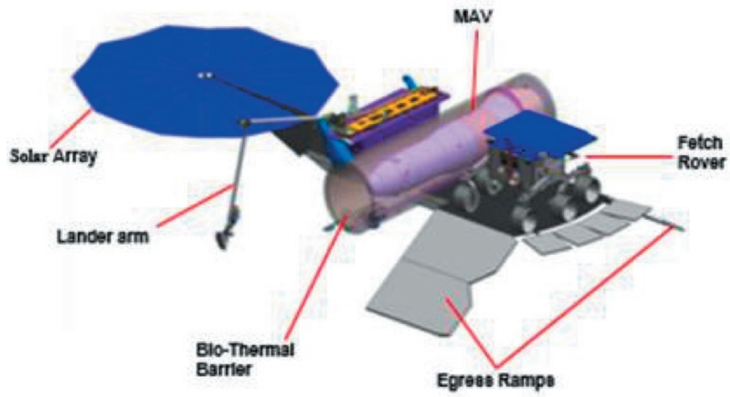
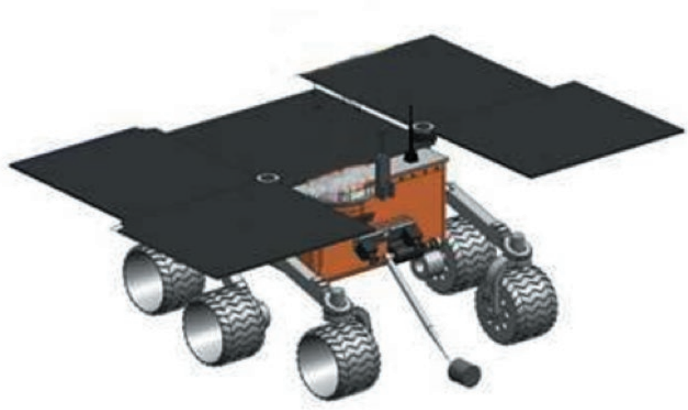


FIGURE 3-6: SRL Fetch Rover concept (Source NASA).

The MAV would be a two-stage rocket using solid propellant motors derived from existing designs. The MAV would include avionics to provide attitude control for both stages and the release of the OS chassis at burnout. The MAV would place the OS chassis in a stable circular orbit with an orbit lifetime of more than 50 years. Figure 3-8 shows a design for this MAV and its accommodation within a thermal enclosure on the platform.

FIGURE 3-7: MER-class fetch rover concept, with simple cache retrieval system (Source NASA).



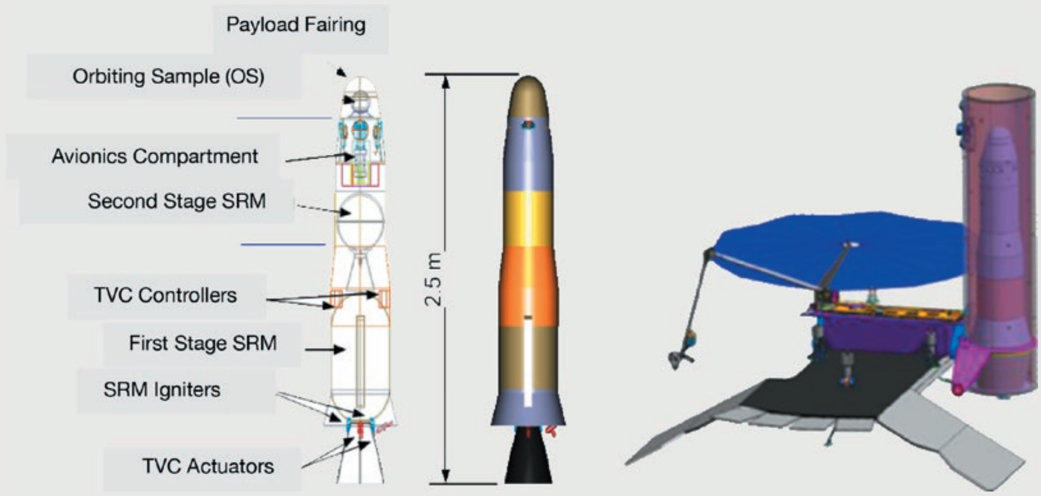


FIGURE 3-8: Notional MAV on the platform lander with its thermal enclosure (in the erected launch position) (Source NASA).

Issues With a Fixed, Platform-based Lander

The 2010 Decadal Survey concept rests on many simplifying assumptions that allow straightforward implementation of the platform lander. Updates to MSR science objectives since then have negated many of those assumptions, complicating planning for the SRL mission. Issues relating to a fixed lander include:

- Roving capability: The 2010 Decadal Survey assumed that the SCR mission would return a completed monolithic cache of samples to the centre of a potential landing ellipse. Assuming a nominal, worst-case, landing-ellipse semi-major axis of 6 km (which would require a significant advance in EDL capability), the maximum round-trip traverse distance for the fetch rover would be 12 km. The SCR mission concept described in this report does not provide for returning samples to a given point. Some SCR studies assume a "go-to" landing site, with regions of interest for sampling lying outside the landing ellipse, dictating that a much greater traverse capability for the sample-retrieving rover. A small rover's traverse capability is limited by its ability to access terrain characterized by the size and frequency of potential hazards, and its sole reliance on solar power, which limits the duration of surface operations.

- Sample retrieval: The Decadal Survey gave little attention to off-nominal or fault case analysis. One significant fault case to consider is retrieval of a sample cache from a non-operating SCR. If the SCR collects a viable set of samples but fails to place them on the surface, a fetch rover could be required to extract them from the SCR. The Decadal Survey's fetch rover concept featured a simple retrieval arm, limited in its ability to extract samples from an SCR. The small size of this fetch rover is not accommodating of a more capable arm. A possible resolution of this issue could be periodic placement of individual samples on the surface for later retrieval.

Mobile MAV Concepts

An alternate SRL mission concept is based on an MSL rover chassis, which would carry the MAV as a payload. This concept does not include a landed platform. The rover/MAV combination is an integrated flight element, landing on rover wheels in the same manner as MSL. Figure 3-9 provides an example of a mobile MAV concept.

The mobile MAV concept was conceived to address some of the apparent limitations of the landed-platform concept. An MSL-class mobility system would be better able to traverse hazardous terrain (accommodating larger hazards) and complete a longer traverse. The mobile MAV concept also eliminates the need for two-way traverse, as the rover would carry the MAV to the samples.

Architectural Options

Two rover options are under study for a mobile MAV: solar-powered and radioisotope thermoelectric generator (RTG)-powered. Each options has benefits and costs. The RTG-powered mobile MAV concept incorporates a durable, stable power system proven on MSL. The RTG could provide sufficient power to perform the necessary traverse and caching operations and would be unaffected by dust and Mars winter. Excess thermal energy from the RTG could be used to provide heat to the MAV, protecting it from the surface environment on the way to the cache site. The primary challenge posed by the RTG powered mobile MAV concept is mass. Current studies indicate that safe landing of an RTG-powered mobile MAV may require additional advancements in EDL capability.

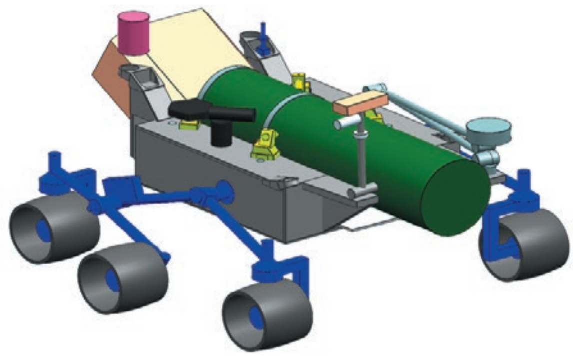


FIGURE 3-9: A mobile MAV concept with the MAV in its launch tube (Source NASA).

The solar-powered mobile MAV would provide the same traverse and sample handling capability as the RTG-powered mobile MAV, with some limitations. Solar arrays could not provide enough power to operate at a reasonable capacity during dust storms or Mars winter. The need for large solar arrays could limit the terrain that is accessible. However, the solar mobile MAV concept would be easier to configure and could be delivered by the heritage MSL EDL stage. Figure 3-10 compares the two configurations.

Key Mission Drivers and Challenges for the SRL Mission Concept

SCR mission performance will be a key driver of the SRL mission. The key SRL mission objective of collect-

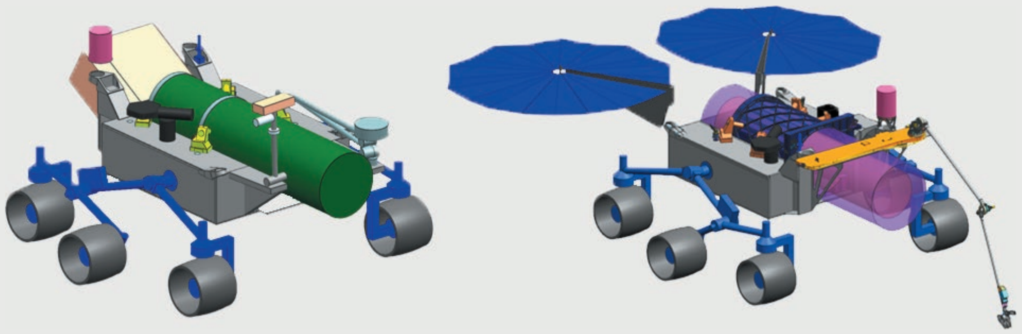


FIGURE 3-10: Concepts for RTG-powered and solar-powered mobile MAV configurations (Source NASA).

ing samples, placing them in the MAV and injecting them into Mars orbit poses multiple challenges:

- Entry, Descent and Landing: Ability to deliver the SRL surface system with the necessary mass in close proximity to samples.
- Traverse Capability: Ability to traverse from landing site to samples and get them to the MAV.
- Sample Collection and Handling: Ability to collect samples and place them into the MAV for injection into orbit, maintaining the integrity of samples and preparing them for Earth return.
- Orbit Injection: Ability to place the OS chassis into a stable long-term orbit for rendezvous.

3.1.2.3 SRO

The SRO mission is the third flight element of the MSR campaign. This mission would collect the OS chassis from Mars orbit, encapsulate it in one or more sealed enclosures to meet planetary protection requirements, and return it to Earth. To meet campaign objectives, the SRO mission must meet the following requirements:

- SRO-1: Retrieve the Orbiting Sample chassis from Mars orbit.

- SRO-2: Encapsulate the OS in a containment system to break the chain of contact with Mars.
- SRO-3: Insert the encapsulated OS into an Earth Entry Vehicle.
- SRO-4: Transport the EEV to Earth.
- SRO-5: Inject the EEV into an Earth entry trajectory.
- SRO-6: Ensure that the interplanetary flight system will avoid Earth entry after delivery of the EEV.
- SRO-7: Ensure that no unsterilized or uncontained martian material will be released in the Earth environment.

Two studies conducted in 2011 assessed the technical and programmatic feasibility of a Mars Sample Return Orbiter (SRO). The two concepts produced include Propulsion Module (PM), Orbiter Module (OM), Orbiting Sample Handling System (OSHS), and Earth Entry Vehicle (EEV) elements. These elements would have the following functions:

- PM: Perform outbound cruise manoeuvres and deliver the OM into Mars orbit.
- OM: Retrieve the OS with a rendezvous and capture system, provide a communication relay to surface elements, return the EEV to Earth.

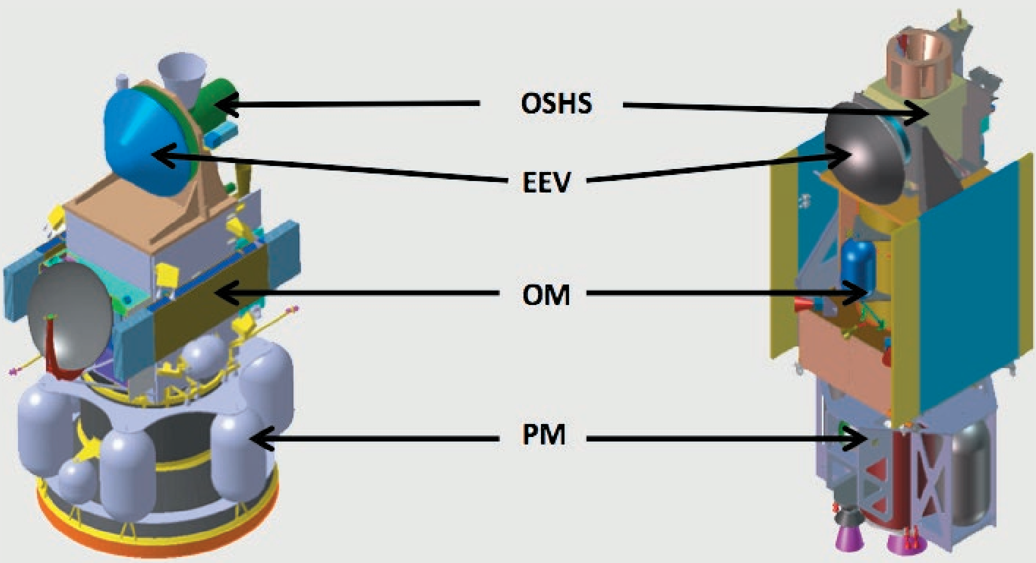


FIGURE 3-11: SRO study configurations (Source ESA).

- OSHS: Transfer the OS to its biocontainment system, seal the biocontainer, and transfer it to the EEV.

- EEV: Perform Earth entry and hard landing (no parachute).

These studies considered the following mission:

- An Ariane 5-class vehicle launches the SRO spacecraft on a 10-month trip to Mars.

- At Mars, the spacecraft performs Mars orbit insertion, followed by an apocentre lowering manoeuver and jettison of its propulsion module. Aerobraking is used to save around 1,000 m/s delta-v for further lowering of the orbit apocentre down to a parking orbit altitude of around 500 km.

- In parking orbit, the SRO waits for the SRL to arrive. The SRO observes the SRL's entry, descent and

TABLE 3-1: SRO spacecraft characteristics

SRO Elements	PM	OM & OSHS	EEV
Power	From orbiter	Solar Array 10 m2	Battery
Communication	-	X-Band to Earth UHF with Mars assets	UHF beacon
Payload	None	Sample handling suite: rendezvous, capture, bio-sealing and transfer	Samples
Dry mass	400 kg (direct escape)	1,000 – 1,100 kg	110 - 120 kg
Wet mass	2,000 kg (direct escape)	2,400 kg	
Total delta-v		4,000 m/s (direct escape)	
Launch mass		4,400 kg (direct escape)	
Ground station		Deep Space Network 35 m antennas	
Enabling Technologies		• Biocontainer (bio-sealing and seal monitoring) • Rendezvous and capture in Mars orbit: robust GNC, sensors (optical and RF), autonomy • EEV thermal protection system: severe heating (up to 15MW/m^2), high reliability • EEV crushable material for hard landing	

landing on Mars. The SRO serves as communication relay for all operating MSR surface elements (lander and MAV, fetching rover). The SRL deploys a sample fetching rover, which collects samples and returns them back to the lander, where they are put into the OS, ready to launch with the MAV. The SRO tracks the MAV launch and the OS release, performs an orbit estimation of the OS, then executes rendezvous manoeuvres up to the final capture of the OS. The rendezvous and capture phase nominally lasts less than 10 days.

- The OS is placed in biocontainment after capture and sealed according to planetary protection requirements. Once sealed, the biocontainer is transferred to the EEV. The OS handling system is then jettisoned to reduce SRO mass and comply with planetary protection requirements.
- The SRO escapes from Mars for a 10-month trip to Earth. At arrival, the SRO releases the EEV for entry at around 12 km/s, followed by a hard landing (no parachute). Samples are retrieved and transferred to the Sample Receiving Facility (SRF) for further storage and analysis.

The SRO design is dominated by high delta-v requirements, which are driven by the following manoeuvres:

- Deep space manoeuver (DSM) of approximately 500 m/s.
- Mars orbit insertion (MOI) of approximately 700 m/s followed by an aerobraking phase.
- Mars escape orbit acquisition of approximately 1,200 m/s and a Mars escape of around 1,000 m/s.

Numerous additional smaller manoeuvres would be necessary to trim the orbit and accomplish rendezvous and capture of the OS. Table 3-1 describes the SRO spacecraft.

Planetary protection requires reinforced failure detection, isolation and recovery; micrometeoroid protection; and additional equipment to protect Mars from forward contamination and Earth from contamination by Mars material. Bio-sealing of samples is triplicated to reach the necessary level of reliability.

The SRO rendezvous concept offers functional redundancy to ensure against a wide range of failures. Capture is performed autonomously.

The EEV is subject to very high heat fluxes due to high entry velocity. Crushable foam is used inside the EEV to limit biocontainer acceleration to 500 g at hard landing.

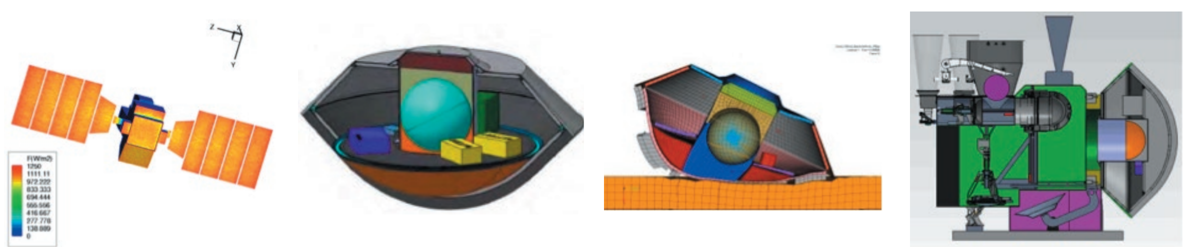


FIGURE 3-12: SRO aerobraking, EEV, Earth hard landing analyses, bio-sealing and transfer concept (from left to right) (Source ESA).

Key Mission Drivers and Challenges for the SRO Mission

To comply with its mission requirements, the SRO faces the following challenges:

- Planetary protection: Planetary Protection Category V, restricted return to Earth (Kminek and Rummel, 2015), requires very reliable systems through all phases to prevent contamination of Earth by the returned sample, or by any other returned uncontained martian material. This requirement particularly affects bio-container and EEV design (the latter presents single-point failures such as its heat shield).

- Rendezvous and capture: A high level of autonomy is necessary to rendezvous in Mars orbit, and a robust rendezvous strategy is required to detect and capture the small OS and cope with possible SRO or MAV malfunctions.

- Earth entry and landing: The EEV has to accomplish safe entry at high velocity (around 12 km/s) and a safe landing without parachute using a crushable structure.

- High delta v: The SRO delta v is high (around 4,000 m/s) and the leverage factor on the launch mass of parts returning to Earth is around 4. Thus the mission is mass-critical.

3.1.2.4 MRSH

MRSH is a ground-based system to receive, analyse and curate returned samples. The MRSH element of the MSR campaign will retrieve and stabilize the EEV and transport it safely to a receiving facility, access samples, and analyse them to meet science and planetary protection requirements. The MRSH element must meet the following requirements:

- MRSH-1: Retrieve the EEV from its landing site, condition the landing site, and transport the EEV to the sample receiving facility for containment and curation.

- MRSH-2: Conduct preliminary analysis of samples for science and planetary protection, including 3-D mapping of samples, e.g. using X-ray tomography, prior to removing individual samples from their containers (McLennan et al., 2012; Kminek et al., 2014). Sample containers must be designed to allow such investigations.

- MRSH-3: Provide curation capability, including long-term storage and sample allocation and distribution and safe transport of samples outside of the primary receiving facility (within containment or sterilised).

A more extensive list of requirements can only be provided after MRSH planetary protection requirements are formalised.

3.1.3 Alternative 4+1 MSR Campaign Architecture

One alternative MSR campaign architecture that could be considered is the 4+1 architecture, if technical or programmatic constraints dictate (Figure 3-13). In this architecture, functions of the SRL element of the campaign are distributed across two flight missions: one to deliver sample retrieval capability and a second to deliver the MAV to the surface. The advantage of this architecture is that it provides additional mass delivery to the surface of Mars, which may be required to fulfil all the functions of SRL. The main challenge of this approach is the requirement for the sample retrieval element to rendezvous with the MAV on the surface of Mars. This requirement demands precision landing capability, or a longer traverse for the retrieval rover and is only feasible if a platform lander with fetch rover is employed.

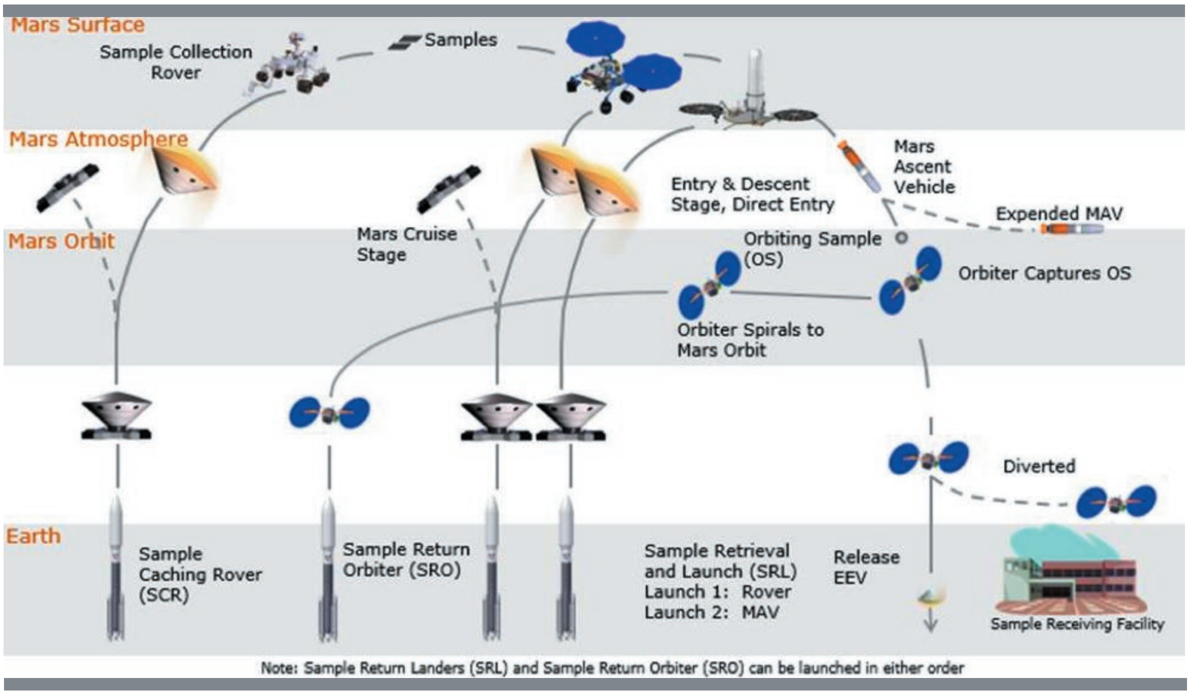


FIGURE 3-13: Alternative 4+1 architecture for sample return (Source NASA).

3.2 MSR Related Technologies

3.2.1 Key Technologies

With its several elements, an MSR campaign requires a wide range of technologies from various technology domains. In preparation for MSR, it is highly desirable to identify all technological needs and remaining technology gaps based on analysis of the current campaign architecture and to develop these technologies as to minimize technical risks. A key goal must be to develop all required technologies for a particular mission element prior to mission implementation (Phase B, at PDR) at least to Technology Readiness Level (TRL) 6, demonstrating critical functions in the relevant environment. Following the iMARS WG Phase 1 report, several space agencies have made significant progress in developing MSR related technologies (see Appendix A.4). Key technologies for the elements of an MSR campaign are:

SCR

- Sample handling and transfer technologies.
- Sealing and storage technology to maintain sample integrity and avoid cross-contamination during all campaign phases.

SRL

- Mars precision landing technologies, potentially with hazard avoidance capabilities, to safely place the MAV and fetch rover close to cached samples.
- Fast Mars rover traverse to minimize the duration of surface operations.
- Mars Ascent Vehicle technologies to launch the OS container from the martian surface into rendezvous orbit.

SRO

- Biocontainment technologies to fulfil COSPAR planetary protection requirements for Category V, restricted Earth return.
- Guidance, navigation, and control (GNC) technologies for autonomous rendezvous of the SRO with the OS.
- OS capture and handling technologies, including transfer, bio-sealing and final transfer to the EEV.
- Reliable high-speed Earth-entry thermal protection system (TPS) technology to comply with planetary protection requirements, which could include protection against micrometeoroid impacts.
- Crushable material technology for impact shock mitigation following Earth entry and hard landing to fulfil planetary protection and sample integrity requirements.

MRSH

- Portable containment infrastructure to safely recover returned samples and transfer them to the SRF.
- Technologies within the SRF to safely handle, analyse and curate returned samples.

Cross-cutting

- Autonomy verification and validation technologies for various mission phases (sampling, roving, transfer, aerobraking, rendezvous, etc.) including the setup of testbeds for various technologies.
- While the development of most of these required technologies has advanced since 2008, some — MAV and bio-sealing technologies, for example—are insufficiently mature and require dedicated development.

While the development of most of these required technologies has advanced since 2008, some — MAV and bio-sealing technologies, for example—are insufficiently mature and require dedicated development.

> *Finding: Technology development efforts should be coordinated amongst participating organisations.*
>
> *Finding: To implement MSR, additional resources must be dedicated to advancing MAV and biosealing technologies.*

3.2.2 Technology Status and Development Timeline

The following section provides an overview of the status of ongoing critical technology developments linked to each mission element. Additional detail on development activities is provided in Annex 6.5.

SCR Technologies

The Sample Caching Rover (SCR) mission will collect and encapsulate samples. The SCR must be capable of accessing sample material, from the surface or subsurface, and encapsulating samples to prevent contamination.

- Sample Collection and Encapsulation: The SCR requires technologies to collect scientifically compelling samples, including regolith and core samples from a range of rock types. Additional capability to access material from the subsurface has been proposed. Once acquired, samples must be encapsulated for return. Key requirements that drive this capability are ensuring the integrity, preserving the orientation of samples, and protecting them from terrestrial (forward) contamination or cross-contamination among samples. Several agencies have been investigating coring drills to collect material from a range of rock types. Sample qualities (fracturing, alteration) are key criteria for evaluating coring technologies. For encapsulation, sealing of the sample container is essential to prevent cross-contamination. Multiple technologies are being investigated, including mechanical seals, crimping and welding to achieve hermetic sealing.

- Planetary Protection (Forward and Return Trip): To ensure sample integrity, the SCR mission must achieve unprecedented levels of cleanliness. Acknowledging that science and planetary protection objectives are intimately linked and that both rely heavily on measurements of organic molecules in returned samples, NASA chartered the Mars 2020 Organic Contamination Panel (OCP) to develop sample contamination requirements for the 2020 mission (Summons et al., 2014). One major recommendation of the OCP is to limit the organic contamination of geological samples to less than 1 ng/g for Tier-I compounds (organic compounds of primary science interest), and less than 10 ng/g for Tier-II compounds (all other organic molecules of potential interest). At the time of writing, a US National Research Council (NRC) ad hoc committee, with international membership, is reviewing the OCP's recommendations. State-of-the-art techniques for sterilizing space hardware – dry heat microbial reduction (DHMR) and low-temperature process using vapour-phase hydrogen peroxide (ECSS-Q-ST-70-57 and ECSS-Q-ST-70-56) – must be augmented for MSR with additional specialized sterilization, precision cleaning and verification processes to ensure that returned samples are not contaminated with terrestrial organic materials.

The SCR mission will benefit from additional technology enhancements in Mars surface mobility (fast traverse, autonomous operations), advanced sensors and algorithms for surface navigation, and advanced EDL capabilities. These advancements may provide access to more scientifically interesting terrain and/or the ability to collect more samples within the operational limits of the mission.

SRL Technologies

The SRL mission will require several key enabling technologies to meet objectives. Some of these technologies, such as the Mars Ascent Vehicle, are unique to the SRL mission, and some are also applicable to other MSR campaign elements. What follows is a summary of these enabling technologies and the SRL requirements that drive their design.

- **Entry, Descent and Landing (EDL) technologies:** To enable delivery of the SRL to the surface with sufficient landed mass and necessary landing precision, a suite of advancements are required. MSL EDL systems can deliver approximately 1,000 kg to the surface with a landing ellipse on the order of 12 km x 20 km. MSL EDL must be able to deliver more mass to the surface. Precision landing is highly desirable to allow landing in close proximity to the sample cache and avoidance of landing hazards. Reducing landing error will enable rapid retrieval of the cache and reduce surface mobility requirements. Current development of low-density supersonic decelerator technology and advanced parachutes will contribute to this capability. Development of hazard detection and avoidance techniques

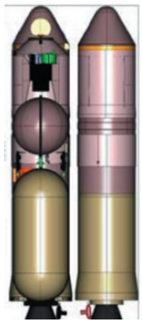
Advanced EDL Parachute technologies. Credit: NASA

and terrain-relative navigation algorithms is also under way.

- **Fast Traverse:** The SRL mission is required to traverse to and retrieve cached samples and deliver them to the MAV. For all architectures, minimizing the duration of surface operations will reduce the risks inherent in operating on Mars and enhance science return. Fast-traverse capability is thus an essential SRL technology if the cache location is not close to an acceptable landing area. Fast-traverse technology is under development, including autonomous optical hazard detection, path planning, and rapid image-processing algorithms.

- **Atmospheric Sample Collection, Handling and Encapsulation:** The SRL will be required to collect an atmospheric sample that will be returned with the surface sample cache. Technology for collecting, pressurising and sealing atmospheric samples has not yet been developed. In addition, technology for handling of the sample on the surface and encapsulation in an Orbiting Sample Container will need to be developed to enable transfer to the SRO. A key requirement for sample handling and encapsulation is maintaining sample integrity from the surface to in-orbit capture.

- **Mars Ascent Vehicle:** The MAV is a critical technology for SRL. A key requirement for the MAV is placing samples in a sufficiently high orbit to remain stable for an extended duration (>50 years), with injection accuracy sufficient to enable rendezvous with the SRO. A key driver of MAV design is the total mass of the OS and any ancillary equipment necessary to assist in rendezvous and capture (e.g. a tracking beacon). Multiple propulsion technologies have been investigated for the MAV, including solid and liquid propellants and single- and multi-stage architectures. Once a baseline design is selected, meeting key environmental requirements will be a developmental challenge.



Notional Mars Ascent Vehicle design. Source: NASA

Progress has been realized on several of key SRL technologies. A decision concerning the baseline configuration for the MAV (lander-based or rover-based) will need to be made in the near future, with focused investments required to further advance the concept.

SRO Technologies

In recent years, considerable progress has been made in developing critical SRO technologies. Three technology domains are mission-enabling:

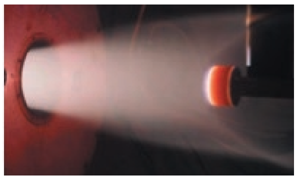
- **Bio-sealing and "break the chain with Mars":** Several onboard sealing techniques have been investigated, which can meet stringent planetary protection requirements to prevent back contamination. A set of highly reliable compressive seals offering triple redundancy, with an associated pressure-based monitoring system as well as a "break-the-chain" procedure, have been verified. Verification of an integrated breadboard is expected by end of 2016.

Biosealing breadboard. Source: ESA

- **Rendezvous and capture:** GNC algorithms have been developed that fulfil rendezvous requirements defined in the current SRO mission scenario. High- autonomy GNC algorithms have recently been tested in a hardware-in-the-loop test bench. In parallel, lidar and RF sensors are under development and testing. Prototype OS capture algorithms and mechanism have been tested on 0-g flights.

- **Earth Entry Vehicle:** Lightweight thermal protection system (TPS) materials have been flight-proven on multiple missions, and new TPS materials are being developed. Further development will focus on the reliability of the TPS in relation to planetary protection requirements. Crushable-structure testing is ongoing (for hard landing).

Capture mechanism breadboard. Source: ESA



Light density TPS material test. Source: ESA

In summary, all critical SRO technologies are progressing, with many in advanced development. However, further investment is required to develop rendezvous-sensor engineering models (EM) and biosealing and seal-monitoring systems. The iMARS WG recommends that SRO technology development focus on these areas.

MRSH Technologies

The Mars Returned Sample Handling element of the MSR campaign will require a range of technologies to safely investigate samples:

- Technologies to quickly find the EEV after it lands on Earth.
- Transportation of the OS container.
- Tools and techniques to open the OS container without (cross) contamination of samples.
- Opening and handling techniques for individually sealed samples.
- Biohazard screening methods.

For this Phase 2 report, the iMARS WG was not required to develop further details of SRF design and equipment. As noted earlier, planetary protection protocols for MRSH will be crucial in defining needs. Once these protocols are developed, recommendations for specific MRSH technology requirements should be elaborated.

3.3 Campaign Timeline

As introduced in Section 3.1, the primary benefit of a multi-mission campaign is that individual campaign elements can be developed independently, improving the potential for international collaboration and clear interfaces between elements. The timeline for implementation of an MSR campaign is driven by the logic of sequential steps (e.g., sampling must be completed before the SRL can take off from Mars). An important constraint is the maximum duration of sample storage on the surface of Mars and in orbit in the OS, which will be driven by sample integrity requirements and sealing technology limitations. Other schedule drivers include:

- Budget (and other) implementation decisions and approvals, which likely will differ across participating organisations (e.g., fiscal years, ESA ministerial conferences, federal budgets).
- Differing development-cycle durations across participating organisations.
- Planetary protection requirements driving integration and testing procedures and development time.
- Timely availability of enabling technologies, depending on approval decisions and required development time.
- Lifetime of campaign elements (e.g., the OS must be in orbit within the lifetime of the SRO).
- Solar conjunction and dust storm seasons, which will affect arrival dates and operations.
- Robustness to off-nominal operations.
- Development and certification of a fully compliant SRF.

A Potential Sequence and Timeline of Elements:

1. The Sample Caching Rover element has to be the first element launched in order to have a set of samples from regions of interest available for retrieval by the SRL.
2. Following a successful SCR mission, launch order for the SRL and SRO must respect the operational lifetime limitations of various campaign elements. The OS must be in orbit within the lifetime of the SRO. It could be beneficial to have the SRO in orbit to provide SRL surface mission support (e.g., communications), observe critical events such as the launch of the MAV and track the OS post-launch.
3. The maximum time separations between SCR and returning elements (SRL and SRO) are limited only by lifetime considerations of the samples, whether stored on the surface of or in orbit around Mars.
4. The SRF must be operational (providing at least a secured storage and initial risk analysis functionality) before the EEV arrives on Earth, ideally up to two years in advance of sample return (NRC, 2009).

No agency has yet committed to implement an MSR campaign. Key enabling technologies will require additional investment to bring them to the appropriate level of readiness prior to the inception of a campaign. Technology developments most likely to affect the timeline for an MSR campaign are the MAV (SRL element) and the biosealing and "break-the-chain" function (SRO element). Technology development is ongoing (see Appendix 6.5), and funding required for these technologies to reach readiness must be put in place at least three years prior to the inception of a campaign.

If an SCR mission were to be launched in 2020, and a decision to implement the SRL and SRO missions were to be made that year, then the best-case date for sample return would be 2031/33. Figure 3-14 shows a potential timeline for MSR with the SRO mission launched in 2026 and the SRL mission launched in 2028. Samples would be returned in 2031. On this timeline, SRL surface operations are limited to less than one Earth year to meet the trans-Earth Injection window for Earth return.

Another alternative would be to return samples in 2033, allowing two Earth years for SRL operations, inserting them into the MAV and placing them in orbit. This option is shown in Figure 3-15.

3.4 Campaign Management

3.4.1 International Agreements and Coordination

An MSR campaign will be an ambitious international collaborative effort. Many countries and agencies around the world have expressed a strong interest in participating. An MSR campaign will require a model for cooperation that is flexible and adaptable and encourages long-term commitments by participating organisations. Such a model will depend on evidence-based examples of public benefits and impact on the space economy.

An MSR campaign will have significant legal implications relating to intellectual property rights, planetary protection (Treaty on Principles, 1967, Article IX), export control, funding requirements and responsibilities, project management, accountability, arbitration, and conflict resolution. A comprehensive governance plan for the MSR campaign will be necessary.

An agreement will be needed on the application of relevant standards (ECSS, ISO). As a starting point, each agency would apply its own standards to elements for which it is responsible. Partners will need to define interfaces, and working groups will be needed to determine the best approach to implementation.

The International Space Station (ISS) offers one collaborative model for international space exploration, including an overarching framework for cooperation with bilateral agreements between individual partners (i.e. intergovernmental agreements that are legally binding). For an MSR campaign, such agreements would include the entire MSR architecture including ground element (MRSH). As an MSR campaign might have over 30 partners, the ISS model might not be workable for MSR. Entering into legally binding treaty-level agreements will take significant time and a strong political impetus from governments.

Another option for collaboration would be a high-level political declaration similar to the Group on Earth

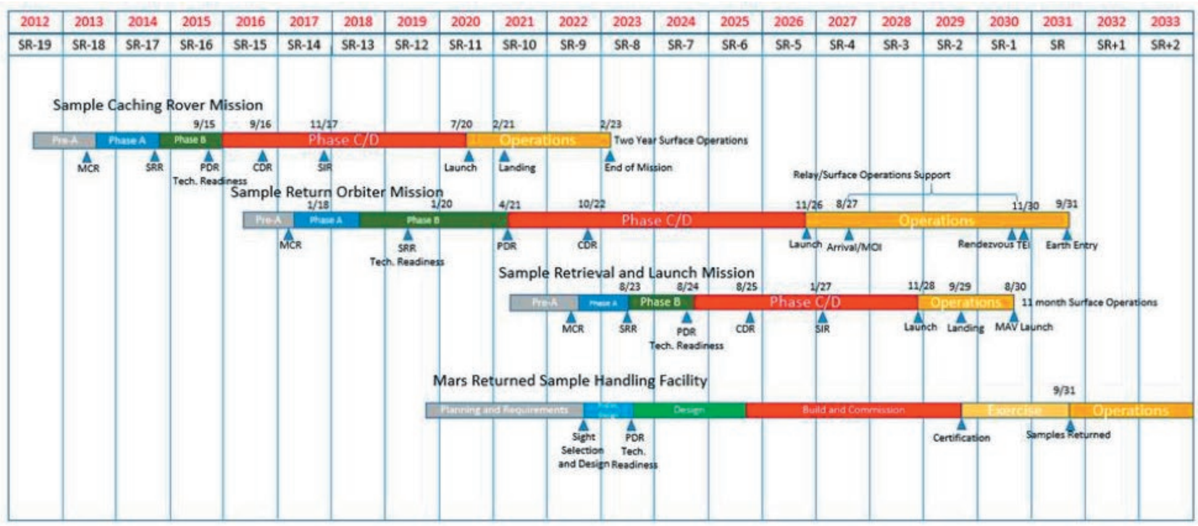


FIGURE 3-14: Proposed timeline for Mars sample return in 2031

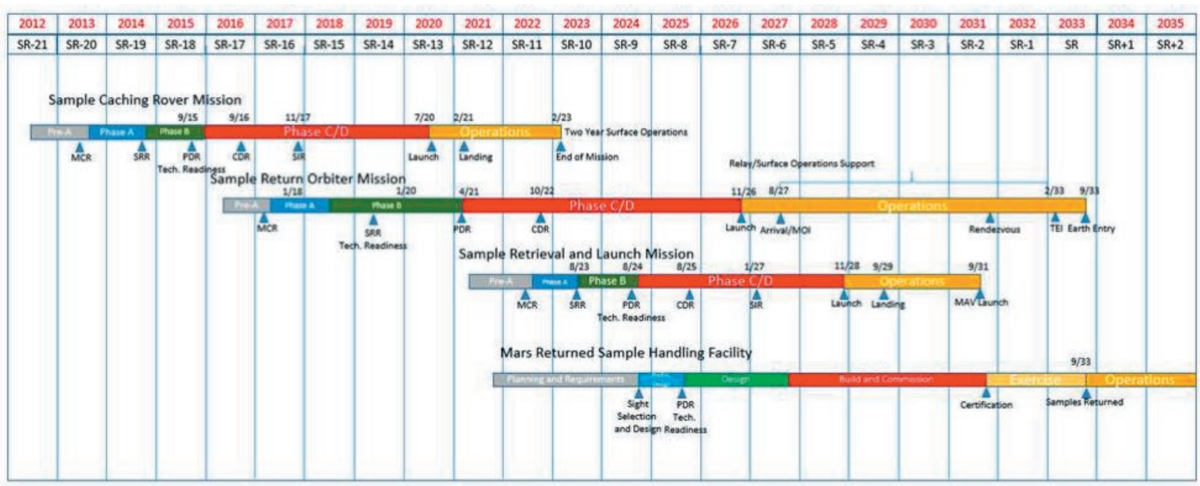


FIGURE 3-15: Proposed timeline for a Mars sample return in 2033

Observations' Global Earth Observation System of Systems 10-Year Implementation Plan, which had significant political momentum (GEO, 2005). GEO, comprising members and participating organizations, was established on a voluntary and legally non-binding basis, with voluntary contributions to support activities.

Memoranda of understanding that are not legally binding but could have ancillary implementing arrangements that are legally binding are also an option.

The CERN model of scientific collaboration can be considered as well. This model allowed partners to share costs and unified a multinational community of scientists. A significant political thrust by the United Nations helped to create CERN. Two months after the U.N. adopted a resolution to create a European

Council for Nuclear Research. Eleven countries signed an agreement establishing a provisional council, and the acronym CERN was born.

As an MSR campaign will be a significant financial undertaking, it will be important as a first step for governments at the highest levels to endorse this campaign. The iMARS WG recommends that an MSR mission statement be developed for endorsement by participating agencies, indicating international commitment to a campaign. A declaration by interested nations would have to be signed, allowing for further development of critical architecture requirements and a governance structure for the mission. As detailed in Section 4, the iMARS WG recommends establishing a virtual MSR Institute as part of the campaign's governance structure.

Finding: Interested nations should sign a declaration of interest in MSR to allow further development of a mission architecture and governance scheme.

Finding: Dedicated programmatic working groups should be created to define guidelines for the application of standards.

Finding: The cooperation model should be flexible and adaptable, encouraging long-term commitments by participation organisations, and allowing partners to contribute in line with their respective priorities and budgets.

3.4.2 Campaign Contingency Management

The principle of architectural robustness dictates that an MSR campaign should be designed such that failure or delay of one element does not jeopardize the entire campaign. A number of rules should thus be followed:

- The campaign sequence should be resilient to delays in development of any one element. Delays could lead to postponing the launch of later elements and/or maximising the lifetime of already launched elements;
- The campaign should be resilient to technical failures, with two types of mitigation actions:
  - Intra-element robustness: State-of-the art design rules should maximise equipment reliability, implement redundancy, establish design margins, etc.
  - Inter-element robustness: failure of a campaign element is recovered by another campaign element. An approach to providing for inter-element robustness is described below.

When defining campaign elements and interfaces, a thorough analysis of possible contingencies and failures and associated mitigation actions must be performed. This analysis should be started in the early phases of the campaign so that implications for subsequent campaign element design can be addressed. What follows are some examples of failures that can be handled at campaign level (considering the 3+1 reference architecture):

- Failure of the SCR after caching operations: can be mitigated by designing the SCR and SRL rovers to ensure that the SRL rover robotic arm is able to retrieve the cache from the SCR. This risk could also be retired by planning for adaptive caching, which would place samples on the surface in incremental lots instead of collecting them on the SCR.
- OS injection by the MAV in an off-nominal Mars orbit: can be mitigated by designing the SRO such that its GNC system and its propellant sizing allows for rendezvous in such off-nominal orbit.
- Late delivery of the OS into Mars orbit due to contingencies during surface operations: can be mitigated by designing the SRO for an extended lifetime allowing sample return in a subsequent opportunity.
- Failure of the SRO before OS capture: can be mitigated by designing the OS for a long orbital lifetime, so that it could be retrieved by a rebuilt SRO.

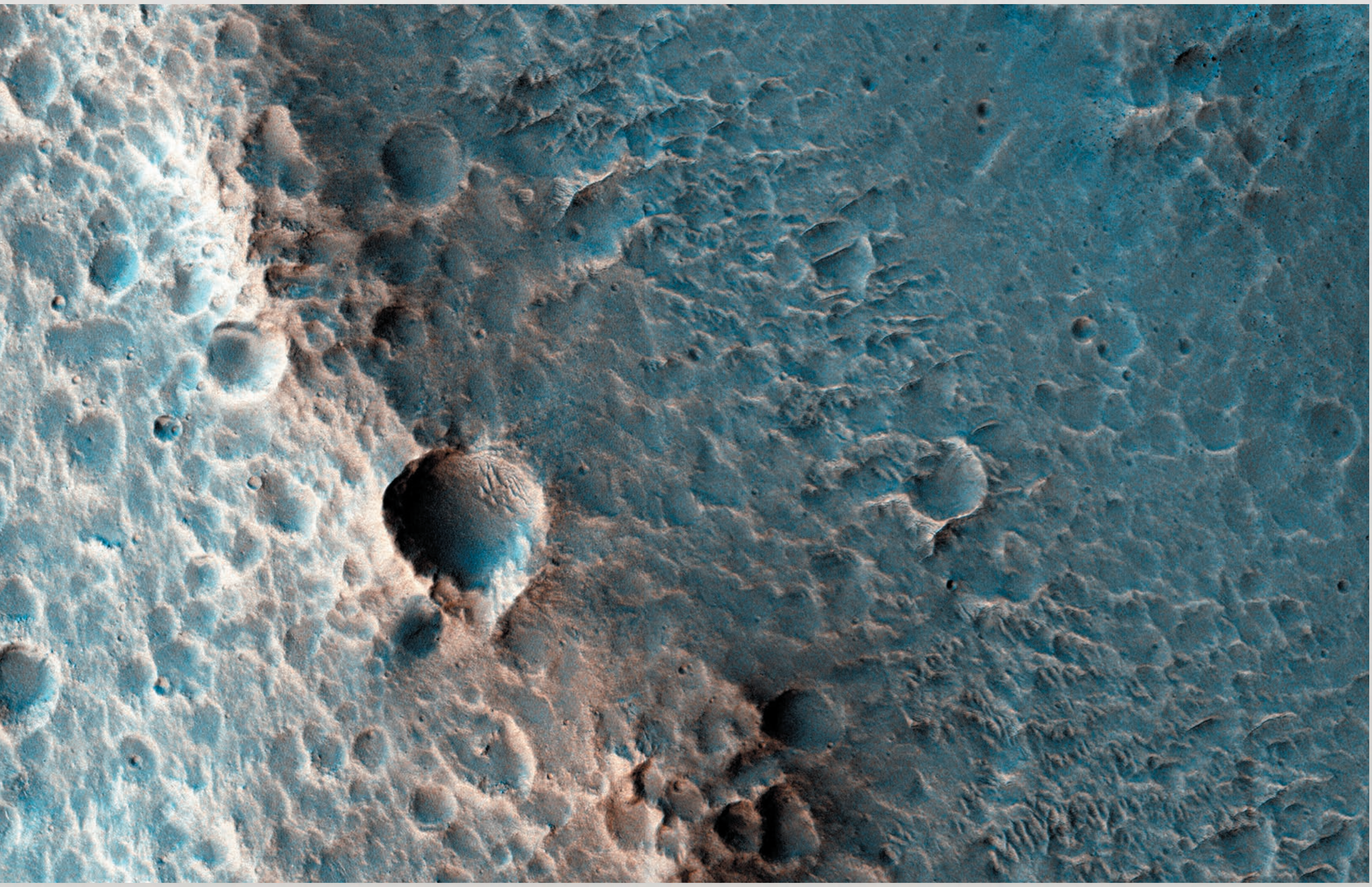
Some campaign element failures cannot be mitigated at campaign level – for instance, failure of MAV during launch, failure of SRO after OS capture, SRO not allowed to return samples due to bio-sealing malfunction. Such failures shall be mitigated by increased design conservatism and validation at campaign element level, to maximise their reliability.

IMAGE

High Resolution Imaging Science Experiment (HiRISE) camera to obtain this view of an area with unusual texture on the southern floor of Gale Crater. This area shown hosts many distinctive landforms in a different part of Gale Crater from where NASA's Curiosity rover is working.

Image credit: NASA/JPL-Caltech/Univ. of Arizona

IV. Sample Science Management Plan



ABOVE IMAGE

This region of Xanthe Terra has mostly been contracted due to thrust faulting, but this local region shows evidence of extensional faulting, also called normal faulting. When two normal faults face each other, they create a bathtub-like depression called a "graben."

Image credit: NASA/JPL-Caltech/Univ. of Arizona

iMARS

The return of samples from Mars is of paramount scientific interest and will be an international undertaking. The Sample Science Management Plan proposed in this report provides a credible structure and process for ensuring that the best possible science is accomplished with returned samples, the Earth is protected from contamination, and pristine samples are preserved for the future. Two guiding principles have emerged for sample science management: open competition for access to samples and proposed research, and as a world endeavour, public transparency and engagement in returned sample handling and scientific results.

The philosophy of 'performing world-class science as safely as necessary' has guided the iMARS WG in preparing this report. With this philosophy in mind, the WG proposes a sample management structure. Roles and responsibilities are outlined, a context is suggested for overall scientific management, and some preliminary ideas are presented for how the cost of such a campaign could be shared. Sample allocation and data policies are addressed, and a curatorial framework is proposed.

4.1 Sample Management Structure

4.1.1 Institute Definition

Overview

An MSR campaign will require the participation and engagement of a multitude of spacefaring nations and thus multinational coordination. In addressing such a challenge, the iMARS WG's Phase 1 report recommended the definition of an International MSR Science Institute (IMSI), which would be tasked to retrieve, house, analyse, and distribute the returned samples as part of the MRSH architecture. The iMARS WG Phase 2 Science / Earth Operations subgroup undertook this task.

Consistent with previous studies (Allwood et al., 2013; Kminek et al., 2014), the subgroup found that MSR science and safety drivers are extremely complementary (see Section 2.5 for a more detailed discussion). Similar measurements will be required for planetary protection purposes and preliminary sample examination. The subgroup determined that science and planetary protection considerations cannot be separated. Thus a sample science institute must accommodate science and planetary protection needs.

> *Finding: An International MSR Science Institute should be established as part of the governance scheme.*

Organizational Structure

An IMSI organizational chart is presented in Figure 4-1 that incorporates safety considerations in greater detail than previously suggested (e.g., Rummel et al., 2002). The institute as described here would function at three different levels:

- Executive: IMSI executives are the key stakeholders of the sample return effort, including representatives from various space agencies, regulatory authorities and appropriate government representatives. Members of the executive are internationally distributed, residing at their home institutions.

- Collocated at Sample Return Facility: The heart of the institute, collocated staff oversee day-to-day operations. Key functions include: a director who oversees sample management; technical branches that satisfy scientific, safety, and curatorial needs; and a corporate branch that maintains facility functions. Note that leadership roles could be filled and work remotely in advance of the SRF location being selected.

- Virtual Teams: Virtual teams are composed of internationally recognized experts in their given scientific or safety fields. These teams will develop the protocols and procedures to be followed by the on-site institute members.

Embedded within the structure are three advisory bodies. Although not formally part of the organization, it is recommended that these groups are established in parallel to serve local and international interests and regulations:

- Science Advisory Board: provides independent science and technical oversight to the institute.

- Back Contamination Board: provides independent regulatory oversight to protect public health and the terrestrial biosphere.

- Public Consultation Committee: provides a mechanism for addressing public concerns.

The iMARS WG is not recommending whether one or multiple SRFs should be built. However, the organizational structure proposed here is sufficiently modular to accommodate either option.

> *Finding: The IMSI science, safety, and curatorial management should be collocated at the SRF, while the implementation of executive level and virtual science teams can be internationally distributed.*

Incorporating the Scientific Community

In addition to defining the institute, the iMARS WG devoted significant effort to identifying entry points for the broader scientific community to engage in the sample return effort. It is important to reiterate that community support for an MSR campaign is predicated on the notion that samples will be accessible to scientists within and external to the SRF and not restricted to those affiliated with institute members. Entry points for scientists are illustrated in Table 4-1.

	Sample Collection	Post-Collection / Pre-Return	Preliminary Examination	On-Site Investigations	Off-Site Investigations
Potential Role	Sample team	Suite-based virtual team	Mars Sample Preliminary Examination Team (MSPET	Guest scientist	
Location	Distributed	Distributed	At SRF	At SRF	At SRF
Selection Process	Competed	Competed	Competed & appointed	Competed	Competed
Activities	Select which samples are collected	Develop sample analysis and handling protocols	Conduct initial physical and geochemical characterization	Perform hypothesis-driven research within the SRF	Perform hypothesis-driven research at home institution
Report Section	4.2.1	4.1.2	4.2.1	4.2.1	4.2.1

TABLE 4-1: Mechanisms by which the scientific community can engage in the MSR effort

4.1.2 Roles & Responsibilities

Institute Council

Analogous to a board of directors, the Institute Council comprises senior stakeholders from participating space agencies and other relevant organizations. The Council is responsible for exercising overall political and financial oversight of the institute and must play a leadership role in:

- Setting the overall governance structure for the institute,
- Ensuring adherence to international laws and agreements,
- Selecting and evaluating the institute director,

- Appointing members of advisory boards,
- Securing funding for institute facilities and operations,
- Reporting on all activities to funding agencies,
- Periodic auditing of the functioning of the director and institute branches, and
- Providing visibility and accountability to the international community.

Science Advisory Board

Following recommendations from the NRC (Committee on Planetary and Lunar Exploration, 2002; NRC, 2009), the iMARS WG suggests that an independent Science Advisory Board (SAB) be constituted with oversight authority. The SAB will ensure that the Council is receiving the necessary advice and recommendations to make informed decisions.

The SAB chairperson should have ex officio status on the Council. Remaining members of the SAB should comprise senior biologists, geochemists, and other experts deemed qualified to oversee the planning, construction, and operation of the SRF and able to avoid conflict of interest (real or perceived). Members would be internationally distributed, participating in on-site activities at the request of the Council. The Council would appoint members to the SAB for varying terms. Overall membership of the SAB could reflect, roughly, stakeholder participation in the institute.

The SAB would be tasked to:

- Support selection of the institute director,
- Perform regular scientific review of SRF planning and construction,
- Formally evaluate the scientific performance of the institute and make recommendations to the council based on its findings,
- Monitor the effectiveness and neutrality of selection processes, and
- Advise the council (and the director) on future strategies.

Back Contamination Board

The drive to maximize scientific return must be balanced against requirements for sample management and safety (Rummel et al., 2002; NRC, 2009). To ensure independent oversight throughout the lengthy and complex process of planning and implementing an MSR campaign, those responsible for planetary protection aspects of sample return should be provided with suitable authority and accountability (NRC, 2009).

The proposed Back Contamination Board (BCB) could be modeled on the Interagency Committee on Back

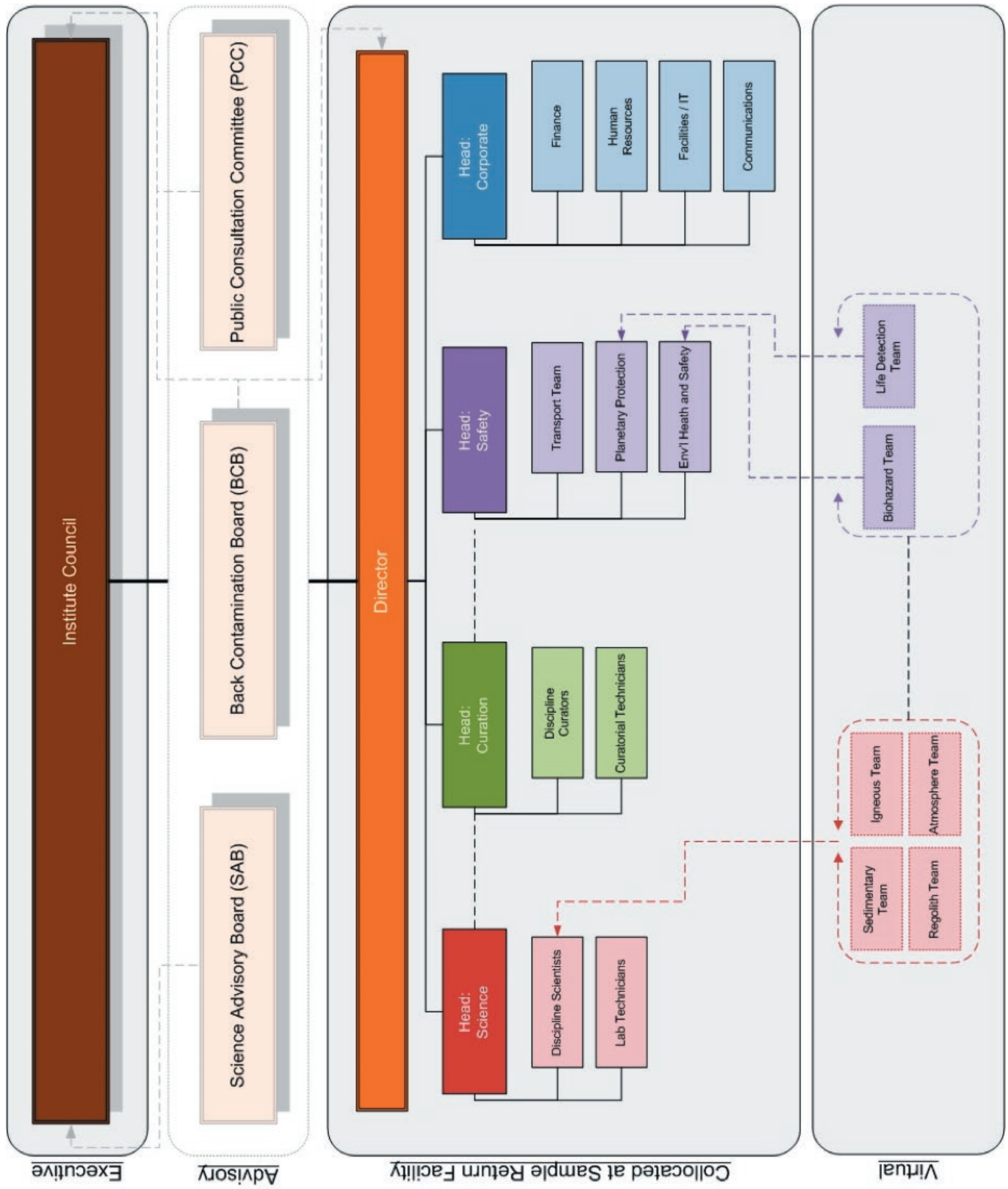


FIGURE 4-1: Proposed IMSI organization chart

Contamination (ICBC) used for the Apollo program. The ICBC was a key element in a comprehensive lunar quarantine program, established to "protect the public's health, agriculture and other living resources" (Johnson et al., 1975). The ICBC was organized under the leadership of public health authorities and included other federal regulatory authorities (i.e., interior, environmental protection, and agriculture).

The BCB should report to the institute director and to council. In this way, the BCB (together with the local planetary protection officer) would fulfil a role similar to product/quality assurance in an instrument development programme. The board would draw not only on internal expertise from science and sample preservation/protection groups but also on external experts to certify external facilities for sample reception. BCB members would be based primarily off-site but would conduct regular site visits, especially during SRF construction and verification. SAB and BCB members should receive honoraria for their services.

Suggested responsibilities for the BCB include:

- Ensuring adherence to local and international safety regulations,
- Conducting audits of the SRF,
- Certifying external facilities for sample reception,
- Certifying release of samples and mission hardware from containment, and
- Reviewing proposals requesting the release of samples from containment.

The size and composition of the BCB would need to evolve during various campaign phases, and be responsive to the results of sample analyses – whether positive or negative.

Public Consultation Committee

The public will want to know about IMSI planning, policies and operations. The Public Consultation Committee (PCC) will be the primary interface between the Institute Council and the PCC. The PCC will be an independent body, responsible for providing public insight into decision making and operations related to the handling and examination of samples and a public voice in the administration of the Institute.

Committee members should represent the interests of the public, would be selected by organisations involved in the IMSI, and should serve limited terms. The chairperson of the PCC would maintain ex-officio status on the Institute Council. The board would provide advice to the Institute Council and the director on activities of interest to the public. The board would serve as a standing interface with the public, provide advisory services to institute leadership on public concerns, and monitor the effectiveness of communication and outreach efforts.

> *Finding: Because public support will be desirable for MSR flight missions and crucial for SRF development, the MSR campaign will require a formal public engagement strategy.*

Director

As the single point of contact between the institute's governing body (Council) and its actual functioning, the role of Director must bridge a variety of programmatic and technical responsibilities. The Director has a highly visible role and must therefore be an internationally recognised scientist, possess extensive management and public relations skills, and intimately understand the safety and security needs of the SRF.

Specific responsibilities for the Director include, but are not limited to:

- Ensuring the scientific excellence of sample analyses;
- Ensuring that sample preservation/protection meets the highest standard;
- Reporting on all activities to external science advisory boards;
- Organizing advisory and supervisory board meetings;
- Implementing necessary health, safety, and planetary protection procedures;
- Keeping the institute within budget;
- Operating the institute according to local laws;
- Representing the institute publicly as required;
- Ensuring full and appropriate dissemination of information on the institute's activities;
- Ensuring transparency of selection processes and the nature of distributed samples; and
- Coordinating the activities of branch heads.

Head: Science

The institute's scientific branch must play a pivotal role in ensuring the quality of sample investigations. As recommended by previous studies (e.g., NRC, 2009), a multidisciplinary science team must be at least partially collocated at the SRF to develop, validate, and perform a rigorous battery of tests. This team would include specialists in the different types of samples making up the various sample suites. The position of Head: Science thus must be filled by a top-level scientist, whose principal remit is to maximize science return from sample analyses. Among other things, the Head: Science will be responsible for:

- Equipping and maintaining a set of laboratories for investigation of the samples;
- Staffing laboratories with appropriate personnel, including scientists and technicians;
- Supervising and instructing administrative staff;

- Organizing the scientific review of proposals for external use;
- Organizing the audit of external laboratories proposing to use samples;
- Reporting on scientific findings to the Director;
- Maintaining a database of scientific findings;
- Advising the Head: Safety of all scientific findings; and
- Responding to requests from the Head: Safety for scientific analyses of samples as requested.

Head: Safety

In line with recommendations from advisory committees (Committee on Planetary and Lunar Exploration, 2002; NRC, 2009), samples from Mars and mission-related equipment returned to Earth will need to be contained and treated as hazardous until proven otherwise. Responsibilities for the Head: Safety include:

- Reviewing and approving plans and specifications for containment and decontamination infrastructure, elements used in the recovery and transportation of samples, and mission-related equipment exposed to Mars material;
- Reviewing and approving procedures and standards for containment and decontamination infrastructure and elements;
- Reporting on safety issues to the Director;
- Overseeing biological and toxicological characterisation of samples;
- Conducting audits and certifying all containment and decontamination infrastructure and elements;
- Certifying personnel working within containment;
- Reviewing and approving operational procedures used under containment on samples, mission- related equipment, or equipment exposed to Mars material;
- Reviewing and recommending the release from containment of samples, mission-related equipment or equipment exposed to Mars material;
- Leading environmental impact assessment and the development of contingency and emergency procedures; and
- Interacting with relevant regulatory authorities.

Head: Curation

Curation of the Mars samples is a critical interface between scientific and planetary protection activities within and outside the SRF. The institute's Curation branch will ensure that samples are handled, sub-sampled, stored and transported in compliance with yet-to-be-determined cleanliness and planetary protection requirements. The Curation branch will be responsible for creating and maintaining a detailed documentary history for each sample, from initial reception through long-term use in scientific studies. This curatorial record must capture every action carried out on samples in addition to relevant information from scientific and PP investigations.

The Head: Curation must be a top-class scientist with a thorough knowledge and understanding of the issues surrounding the curation of extraterrestrial materials. The Head: Curation will be supported by a team of expert Discipline Curators who have extensive knowledge of science and sample handling, sub-sampling and preparation techniques for different types of samples (e.g. igneous materials, sedimentary materials). The Head: Curation will be responsible for:

- Equipping and maintaining curation laboratories, including sample storage areas, sample handling and preparation equipment and sample packaging and transport;
- Staffing curation laboratories with appropriate personnel, including Discipline Curators and curatorial technicians;
- Supervising and instructing administrative staff;
- Organizing the review of available samples;
- Reviewing sample management plans;
- Fulfilling curatorial orders per instructions from the SARB (see Section 4.2.3);
- Interacting with the Head: Science and Head: Safety;
- Reporting on curatorial activity to the Director;
- Ensuring that samples are managed correctly in external laboratories through audit and compliance with protocols; and
- Maintaining a comprehensive curatorial record capturing all aspects of sample interaction within and outside the SRF.

Head: Corporate

The role of the corporate branch is to ensure efficient day-to-day operations of the institute. The size, scope, and remit of this branch are expected to scale with the complexity of the facility. This branch should therefore be organized and staffed only after final facility needs are defined. The Head: Corporate will be responsible for:

- Coordinating human resource needs (payroll, benefits, etc.);
- Overseeing financial management and accounting;

- Supporting the required information technology services;
- Developing and executing communication strategies;
- Reporting operational issues to the Director; and
- Maintaining the security and cleanliness of the facility.

Virtual Teams

Previous studies have recommended that samples selected for return from Mars will be collected as coherent, geologically related suites (e.g. sedimentary, igneous), the exact details of which will likely depend on the final landing site (MEPAG ND-SAG, 2008; McLennan et al., 2012). In turn, the manner in which samples are analysed and distributed, the process by which they are allocated, and criteria by which they will be deemed (or made) safe for uncontained distribution will vary. That is, igneous rocks will be treated differently than sedimentary rocks, hydrothermal samples, regolith and gas.

Accordingly, it will be necessary to formulate and publish a set of peer-reviewed "suite-specific sampling strategies" documents in advance of the samples being returned to Earth[3]. These documents would outline methodologies by which samples will be subdivided and the manner in which measurements will be conducted. For example, the documents might state that the preferred manner of subdividing sedimentary samples should be across bedding or other structure or specify how atmospheric gas should be extracted from the reservoir. Different samples would also have different requirements for storage, packing (for transport), etc. – gas versus rock being the most obvious example – and these requirements should be established ahead of time. Initially these documents could be produced based on measurements made on Mars, then periodically updated by a peer-review process after return and further characterisation.

Within the IMSI Science Branch, a Discipline Scientist (DS) would be assigned to each sample suite. Each DS would take the lead in assembling a group of experts to develop, write and distribute these sampling strategies. Group members could be distributed internationally and maintain residence at their home institutions, thus forming a "virtual" team responsible for:

- Writing the suite-specific sampling strategy,
- Maintaining and updating the strategy as needed, and
- Consulting on other appropriate IMSI matters requiring scientific input.

The sampling strategies would form a "roadmap" for designing preliminary examination protocols, sample subdivision strategies, and analytical priorities and would also be used by sample allocation committees as critical criteria in approving sample allocation (see Section 4.2.3).

These documents would be analogous to the "site-specific sampling strategies" employed by international ocean drilling programs for each drilling expedition.[3]

> *Finding: The organisation of the science teams, sample allocation, and test protocol development should be specific to each sample suite returned by the mission.*

4.1.3 Science Management

Initializing Scientific Leadership Positions

Developing the IMSI's science leadership structure will pose a variety of challenges, many of which relate to real or perceived conflicts of interest between the Institute Council, the SAB, and the Director. The Council will have to work with the SAB to ensure selection of the best directorial candidate. However, the Council may require additional technical expertise to populate the initial SAB. Hence, initiating the leadership structure development process fairly and openly will be challenging. Possible options each have advantages and disadvantages:

- Council identifies 4-5 senior-level persons who would propose the first Director of the institute to Council using an appropriate and transparent mechanism.
    - This senior-level committee would serve as a temporary SAB. Thus Council would have to have clearly defined criteria for selecting appropriate members.
- Council issues an Announcement of Opportunity to apply for leadership positions and asks an external body to review those applications and make a recommendation.
    - Possible external bodies include the International Space Science Institute, European Science Foundation, and U.S. National Science Foundation. The national membership of these bodies is limited, however, so this option might not be acceptable to Council. Council could provide guidelines on reviewers.
- Council defines requirements, issues an Announcement of Opportunity for applications, constructs a short-list (perhaps using an external recruiter), and then requests letters from 8-10 senior persons in the field comparing the candidates.
    - This system is often used in universities. However, it is not fully transparent and can be extremely slow. The key advantage of this option is that Council would retain full control over the decision-making process.

A process for selecting the Director is proposed in Figure 4-2.

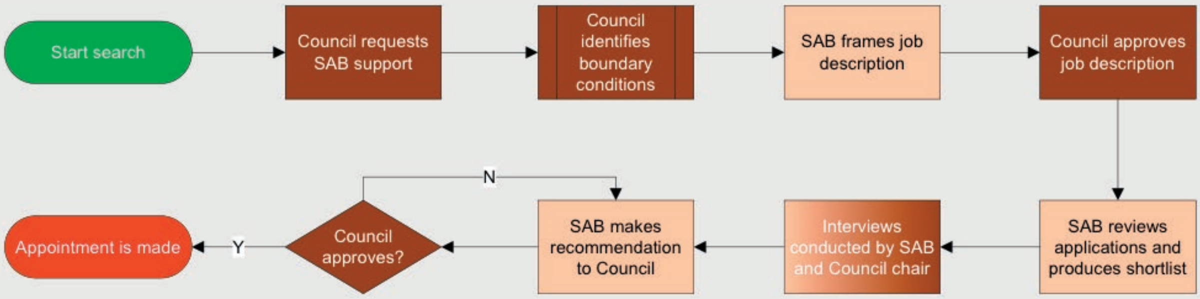


FIGURE 4-2: IMSI Director selection process

Director Selection and Rotation

Development, construction, and initialisation of the SRF could take up to a decade or more (Rummel et al., 2002; Beaty et al., 2009; NRC, 2009). It will be extremely important to name the IMSI Director early in the SRF development process, as his/her input and leadership will be required during ramp-up activities. It is likely that top candidates for Director could only be attracted if they would be able to play a role in facility design.

The Director should be subject to term limits, and rotation at IMSI senior levels should be encouraged. Branch Heads should be given no automatic priority in the succession as Director. While Branch Heads are likely to be well qualified for the post of Director, they should pass through the selection process like any other candidate, without any special consideration.

4.1.4 Facility Needs

Unprecedented Quality Standards

The facility to accommodate Mars samples will be unlike any currently in existence. Unlike typical BSL-4 facilities, the SRF will not only have to protect Earth's environment from samples but also protect samples from Earth's environment and cross-sample contamination (Rummel et al., 2002; Committee on Planetary and Lunar Exploration, 2002). Whereas typical BSL-4 facilities rely on a positive pressure differential to prevent the release of potentially harmful organisms, planetary-sample receiving facilities require a negative pressure differential to prevent sample contamination. Thus the SRF must be a BSL-4 facility contained within a Class 10 clean room (or vice versa) (Figure 4-3).

Although a number of designs have been developed for this sort of containment facility (Beaty et al., 2009), such a facility has yet to be built. However, existing ultraclean forensic BSL-4 facilities, such as the National Biodefense Analysis and Countermeasures Center (Fitch, 2011) in the United States, may provide useful guidance in developing final SRF designs.

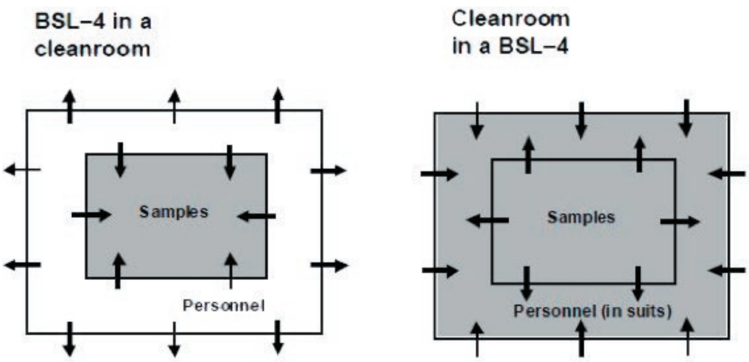


FIGURE 4-3: Options for incorporating biological contamination control within a cleanroom setting, with arrows indicating gas flow pressure differentials (modified from Figure 1 of Rummel et al., 2002)

Adaptability

SRF design and infrastructure should be highly adaptable in terms of both space and purpose for several reasons. Although the general nature of returned samples should be well understood from measurements made on Mars at the time of collection (MEPAG ND-SAG, 2008; Pratt et al., 2010; Mustard et al., 2013), their exact condition (sample integrity) will not be known until they are returned. Thus strategies for extracting, analysing, subdividing and distributing samples must be flexible.

Instrumentation to be housed in the SRF will likely be chosen and in place at least two years in advance of receiving samples (Table 4-2), thus limiting the facility's initial capability to conduct state-of-the-art analyses. The facility will need to add new instrumentation and decommission outdated equipment as understanding of the samples progresses and technology advances. Over time, it is likely that the SRF will release more and more of the samples from BSL-4 level containment and slowly transition from containment and characterization to conventional analysis and curation. It is also possible that the SRF may be used for storage and/or preliminary examination of subsequent returned planetary samples or for terrestrial samples that require similar biosafety and cleanliness standards (e.g., Antarctic lake drilling).

Major Design Drivers

While general recommendations regarding SRF safety and cleanliness needs can be articulated now, specific design requirements cannot be set until a number of decisions are finalized. Factors highlighted in Figure 4-4 will affect the overall size and cost of the SRF. Two of these factors will likely have the most influence: planetary protection protocols, which will determine the size and complexity of the containment area; and sample suite protocols, which will affect the types of instrumentation to be housed at the facility.

Although resource requirements will likely not be determined until the MSR campaign has been approved and the location of the SRF determined, efforts should commence now in the international community to task working groups with setting appropriate safety and science protocols.

Potential Development Timeline

The iMARS WG proposes an optimistic timeline of twelve years to build a fully operational SRF and put a reliable science operations team in place there (Figure 3-14; Figure 3-15; Table 4-2). This timeline is slightly longer than, but consistent with, those proposed in other studies (e.g., Rummel, 2002; Beaty et al., 2009; NRC, 2009). The estimate is based in part on the following assumptions (see Rummel et al., 2002 for additional assumptions):

- If the IMSI is to recruit the best possible Director and Heads of Science and Safety, it must allow them to take part in all facility designs and hirings;

- A basic SRF design will have to be completed before an SRF location or locations can be chosen, to ensure compliance with local requirements and environmental laws; and

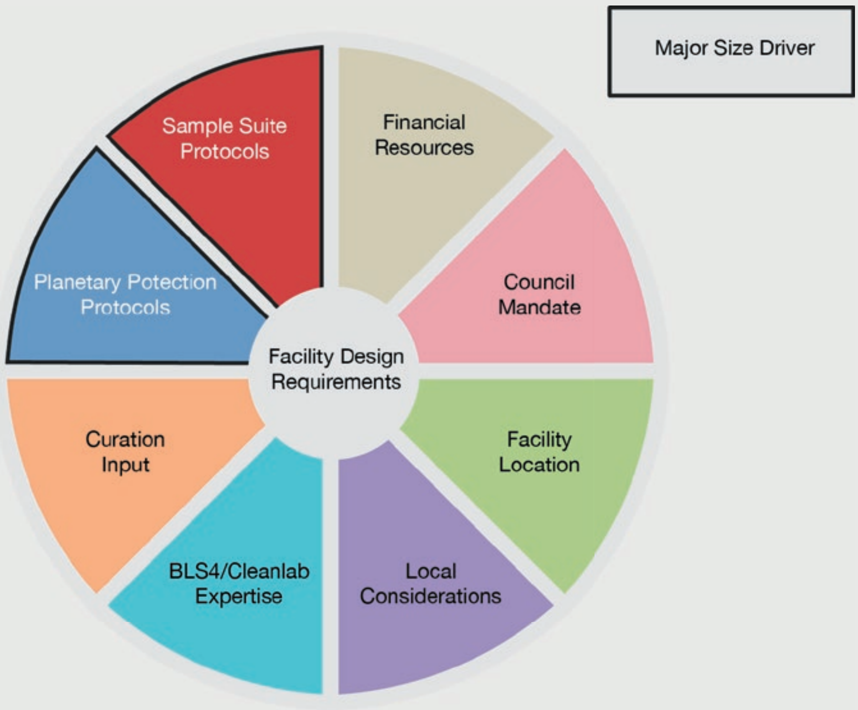


FIGURE 4-4: Factors that will influence SRF design and cost.

- The SRF must be fully functional for two years prior to receiving Mars samples (NRC, 2009).

IMSI should initiate communications with all stakeholder groups early on about the risks and benefits of sample return and the SRF itself to address potential concerns. Continual communication with public interest groups should be maintained throughout the SRF development process. Additionally, IMSI should engage the exising biosafety community (e.g., Center for Disease Control) throughout the design and consultation process.

YEAR	EVENTS
Year X	Funding is in place; negotiate staffing of Institute Council and initiate searches for SAB, BCB, and PAB members
Year X+1	Executive positions (Institute Council, SAB, BCB, and PAB) in place; initiate search for Facility Director
Year X+1.5	Facility Director in place; initiate searches for Science, Curation and Safety Heads
Year X+2	Leadership team in place; initiate searches for key personnel required for SRF design (multiple positions)
Year X+3	Begin design of SRF, including preparation of draft protocols for preliminary examination of samples, needed to design facility (allow two years based on Lunar Receiving Laboratory experience). Site selection process commences for the SRF
Year X+5	SRF design in place
Year X+6	Begin SRF construction (allow two years, based on BSL-4 experience, but may be less or more)
Year X+8	Begin SRF analytical laboratories construction (allow one year); begin analytical instrument selection process (this should be left as late as possible to ensure cutting edge facility)
Year X+9	Install and carry out specifications testing on laboratory instrumentation
Year X+9.5	Carry out verification and validation of facility and laboratories
Year X+10	SRF completed and "ready" to receive samples; carry out operational readiness testing
Year X+12:	Mars samples delivered to SRF

TABLE 4 -2: Projected timeline for design, construction, and testing of the SRF.

The extended timeline required for SRF development may pose a significant programmatic challenge. For example, Figures 3-14 and 3-15 suggest that funding and approvals for SRF development would need to be secured shortly before or immediately after launch of the SCR mission. Decision makers would thus need to have committed to the SRF (at least to early stages of development) before either the SRL and SRO missions have been confirmed.

Alternatively, if SRF approvals are only secured after the third flight missions are underway, the return of samples to Earth would be delayed by nearly a decade. Such a scenario would add significant risk to sample stability and lifetime requirements.

As a result, a stepwise solution may be required. In the first stage, minimum requirements for the containment of returned samples would be defined, and approval could be sought for the necessary infrastructure. After assurance that the baseline safety needs would be met, further stages of planning could outline a pathway for instituting the surrounding facility and equipment to perform subsequent investigations. The iMARS WG thus recommends that the Planetary Protection Protocol clearly define minimum standards for the safe reception of the samples on Earth.

> *Finding: A detailed implementation plan should be put in place as soon as possible for designing, constructing, and operating the SRF. As part of the plan, minimum requirements for safely receiving the samples on Earth should be clearly defined.*

4.1.5 Institute Cost-Sharing Model

Funding Phases

To better understand, plan for, and secure necessary funding for IMSI, the iMARS WG examined expenditures divided into four distinct phases (Figure 4-5).

As noted above, Phases 1 and 2 will take no less than seven years (Committee on Planetary and Lunar Exploration, 2002) and potentially up to 12 years or more. Such a development schedule implies a significant investment prior to the return of martian samples. Thus Phases 1 and 2 should be costed using techniques and metrics similar to those used for flight missions.

Total operational costs for the SRF (Phase 3) will be dependent on facility design and size. While these factors are not yet certain (see Section 4.1.4), rough-order-of-magnitude estimates can be made by analogy. For example, the European Southern Observatory, with a staff of approximately 680 in 2013, had an annual operating budget of €130 M (US$144 M) (ESO 2013). The SRF, with heightened security and safety standards, clean room maintenance, and upgrades of equipment behind containment, will likely require a comparable investment.

Over time, decommissioning of containment facilities can be foreseen if analyses show that none of the samples pose a threat to humanity. At that point, the primary function of the SRF would transition from planetary protection to curation and sample distribution. Thus the cost of rundown activities (Phase 4) should be taken into account during SRF planning.

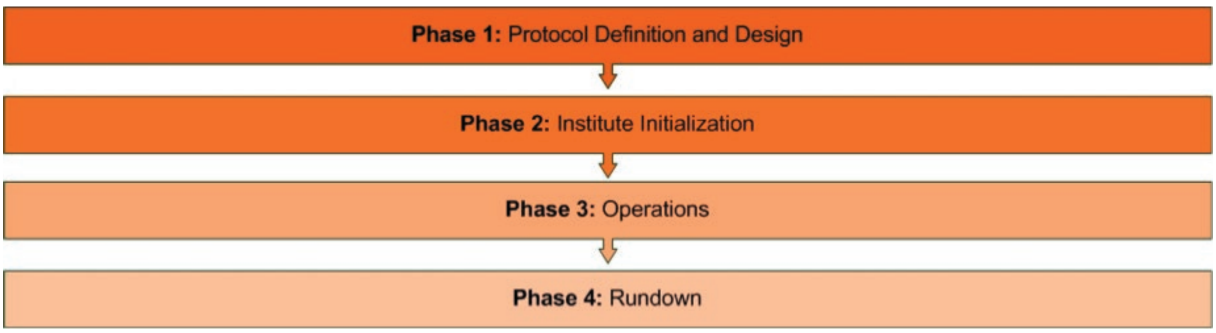


FIGURE 4-5: Projected funding phases for the IMSI.

Cost-Sharing Philosophy

A primary challenge of the MSR campaign is ensuring that each participating country receives a return proportionate to its contribution. While MSR is intended to be a worldwide endeavour, no means yet exist by which costs and contribution can be measured. Measuring the value of contributions from different countries will be particularly challenging considering buying power, no-exchange-of-funds rules, technology transfer issues, and external procurement issues. Hence, direct financial measurements probably will not be adequate.

One way to resolve these issues may be to introduce a fictitious measurement unit to attribute a relative value of each mission element. Once the MSR campaign is defined, mission elements become something of a shopping list. When an agency agrees to build a particular element, it might cost less (or more) than the assessment in the fictitious unit. However, the overall value to the MSR campaign would remain unchanged. In essence, partners would make commitments to supplying a particular piece of hardware irrespective of how much it would cost to produce in any given currency.

Under the proposed model, agencies' participation in the MSR campaign would be determined relative to the value they have contributed in the fictitious unit. This arrangement will require a mutually agreed-upon mission scenario and accurate definition and valuation of mission elements well in advance, negotiated via multilateral discussion. Partners will have to agree on objective criteria for costing mission elements before the MSR campaign begins. Despite challenges, this approach also would offer several advantages, as it would:

- Serve as a quantifiable measure of contribution that is not reliant on currency fluctuations and variances;
- Play to the strengths of different agencies, as each would aim to contribute what they are efficient at; and
- Avoid the no-exchange-of -funds issue.

Previous international cost-sharing space exploration endeavours have relied upon return of some tangible benefit proportional to the original investment (e.g., crew time on the International Space Station, observing time on the James Webb Space Telescope). In the case of MSR, an immediate assumption may be that access to returned samples be proportional to a country's contribution.

However, the iMARS WG strongly contends that sample access should not be the commodity that is portioned out. First, proportional access contradicts the WG's assertion that scientific excellence be used to determine who conducts a particular study. Moreover, not all samples will have the same perceived value (e.g., those containing organic molecules may be more heavily sought). Therefore, attributing a monetary assessment to each sample would likely be more contentious than evaluating the scientific merit of a particular investigation.

Following the model of Hayabusa 2, the WG thus recommends that an agency's or country's investment be reflected in appropriate representation on IMSI's governing council and thus pro rata membership in the decision-making process. Given the number of countries likely to participate, it is unlikely that all members would be represented at all levels of decision-making. Plausibly, those providing larger contributions would be seated on the IMSI Council, with representation at other levels (e.g. advisory boards, allocation committees) from all partners. The details of such arrangements would be determined via multilateral discussions as the relative campaign contributions become formalized.

Should countries or agencies wish to join the partnership after the campaign has begun, they would be subject to an initiation fee. Those proceeds could be used for activities beneficial to the overall sample return effort, such as enhancements to the SRF. This approach has been employed by the European Southern Observatory, for example.

> *Finding: Access to samples should be driven by scientific excellence, independent of the financial contributions of the bidder's home country. Proportional return could instead come in the form of membership in IMSI decision-making bodies.*

4.2 Science implementation

4.2.1 Science Operations

Sample Selection

The value of returned samples depends greatly on expert input, not only in the science of selecting samples to be collected but also for planetary protection and curation. For the SCR element of the MSR campaign, the iMARS WG recommends that mission planners seek outside experts for advice during development and surface operations. Mars 2020 mission planners, for example, established a Returned Sample Science Board comprising representatives of the expert community of scientists, planetary protection experts, and curation practitioners to advise sample handling/caching engineers during hardware and operational-protocol development. The Mars 2020 team will hold an open competition for sample scientists who will join the mission science team and assist in selecting samples for return.

> *Finding: Sample science, planetary protection, and curatorial expertise should inform the sample collection mission development.*

Philosophy and Approach for Managing Returned Samples

Ground-based MSR science operations will be primarily under the purview of the Head: Science, working closely with the Head: Safety and Head: Curation. Senior leadership will have to establish formal "rules of the road" for IMSI personnel, analogous to those used for many planetary missions, establishing among other things the rules governing publication rights and obligations.

In developing procedures and making decisions for science operations and the distribution of samples and data, IMSI leadership should make every attempt to ensure that external peer-review processes are in place. For example, preliminary analytical work dealing with planetary protection will rely heavily on highly standardized protocols. The protocols themselves should be peer-reviewed, and adherence to those protocols (including making any necessary adjustments) should also be periodically reviewed (NRC, 2009).

One of the most important "lessons learnt" from the Apollo program is the need to provide adequate time for establishing and implementing sample management policies and requirements (Alton et al., 1998). Accordingly, it is exceptionally important that IMSI policies be in place well ahead of sample return as, upon delivery, the samples will likely be accessed by different groups of investigators. The Mars sample management plan must be rigid enough to ensure sample safety while accommodating the diversity of researchers expected to work with the samples (Figure 4-6).

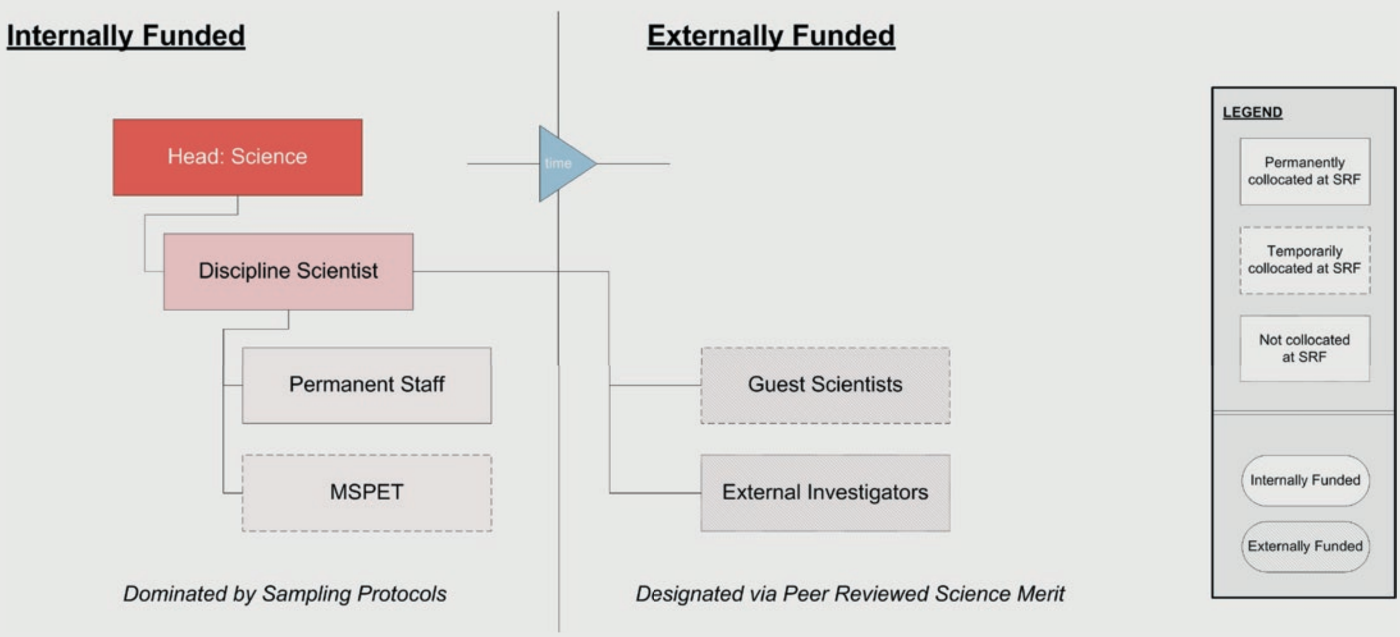


FIGURE 4-6: Individuals and groups expected to require and/or request access to returned samples

Discipline Experts

Returned samples will be handled in very different ways in terms of storage, subdivision, scientific expertise, likely analyses and criteria for sterilization and/or general release from containment (McLennan et al., 2012). The iMARS WG recommends that each suite of samples be assigned an on-site Discipline Scientist and Discipline Curator, each with a permanent staff. Similar to staff scientists in organizations such as the European Southern Observatory, IMSI discipline experts will have an intimate familiarity with and understanding of local instrumentation, possess extensive experience in determining what is and is not possible with the samples, and play a key role in supporting experiments conducted on the samples.

Each Discipline Scientist will serve as the lead for his/her respective virtual team (Section 4.1.2) and be responsible for delivery and maintenance of appropriate sampling strategies. Requirements for analysing different samples flowing from the sampling strategies will need to be reflected in the various analytical laboratories, and discipline teams will need to be directly involved with the operation of those laboratories. In addition, planetary protection requirements will demand separate, specialized expertise (e.g., life detection, biohazard evaluation). Those experts will need to interact closely with specialists assigned to the sample suites to ensure the best and most efficient evaluation of samples prior to release.

The iMARS WG recommends that analytical needs and planetary protection considerations should all be reflected in any operational structure for scientists working on Mars samples. Figure 4-7 provides a "strawman"

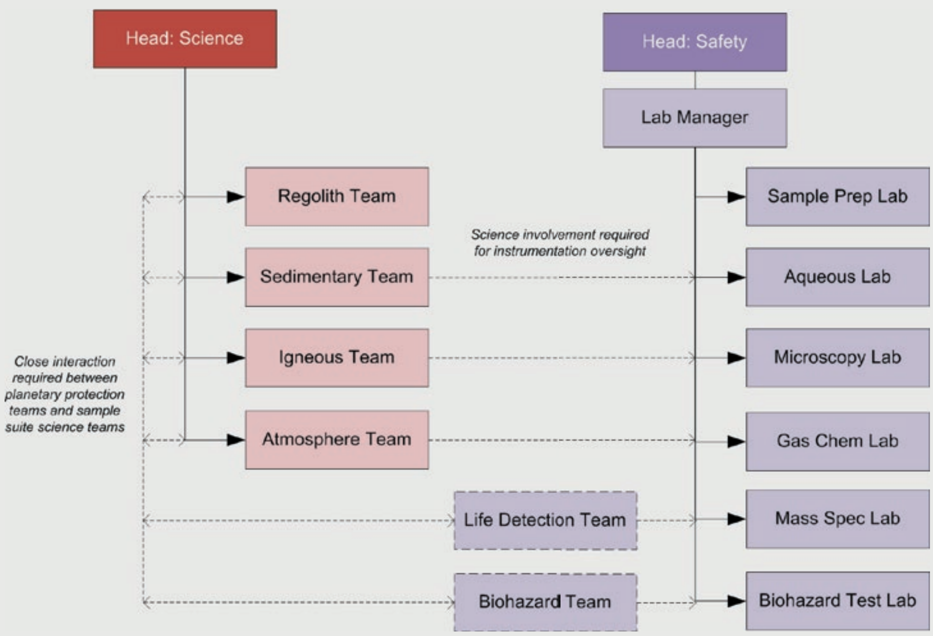


FIGURE 4-7: "Strawman" organizational structure of science teams and analytical laboratories housed within the SRF

example of a possible operational structure in which discipline experts and their teams interact closely with analytical labs under the direction of a Laboratory Manager (reporting to Head: Safety) and are informed by appropriate members of the Safety Branch.

Preliminary Examination Team

During the early stages of sample examination, each Discipline Scientist would also oversee a Mars Sample Preliminary Examination Team (MSPET). Each MSPET would comprise a group of scientists, competitively chosen, who would perform preliminary sample characterization. Each team would work closely with the Safety Branch for planetary protection. Specific roles and responsibilities should be defined in the Planetary Protection Protocol.

Ideally, MSPET members would be selected by peer review. However, it is possible that some necessary expertise may not be selected by this method. Thus IMSI should retain the right to "top up" science teams with needed expertise, by direct invitation, with necessary oversight in place to ensure transparency.
The size and duration of these teams will depend on the scope of analytical facilities in the SRF and criteria employed for preliminary sample characterization, life detection, biohazards, sample sterilization, etc., all of which are TBD. The MSPETs would spend time both in residence at the SRF and at their home institutions, working remotely.

It is likely that the MSPETs will be under great pressure to produce data and may have insufficient time to write up results for publication prior to pre-set deadlines for data release (see Section 4.2.4). Accordingly, the iMARS WG suggests a process by which MSPET scientists would be provided with financially supported time away from SRF obligations to prepare papers for publication. (This process might also help mitigate the fatigue issue discussed in Section 4.2.2.)

Guest Scientists

After preliminary examination is complete, members of the broader scientific community will likely want to work with the samples, even while they are still in containment. IMSI should thus be prepared to accommodate a Guest Scientist Program. Like Participating Scientist programs established for many NASA planetary missions or telescope facilities, the IMSI Guest Scientist Program would select external investigators through a peer-review process based on scientific excellence and compatibility with ongoing investigations.

To ensure alignment with prescribed sampling strategies, Guest Scientists would be encouraged to maintain an association with one of the institute's Discipline teams. Guest scientists and their research teams would supplement the work of the MSPET by conducting more specialized analyses than those done during preliminary characterisation. Guest access to samples and unreleased data would be limited to that which is related to their proposals.

If a single international funding agency is not set up for Mars sample studies, research alternatively could be funded by the national science foundations of participating partners. It is possible that IMSI could provide in-kind support for accommodations and other local considerations.

External Scientists

Not all Mars sample science investigations will take place in the SRF. It has been argued that the majority of investigations should be conducted at external facilities for a variety of reasons. For instance, not all researchers will be able to relocate to the SRF for extended periods of time. Moreover, it is likely that many world-class facilities will have superior analytical capabilities compared to the instrumentation available at the SRF, and any such disparity in capability is likely to increase over time.

As a result, IMSI must develop an extensive and comprehensive External Scientist program where scientists and their research teams could acquire samples for off-site research through a clearly defined sample allocation process (see Section 4.2.3). Participating national and international science foundations would be expected to fund these investigators.

External Scientists would carry out most of their work away from the SRF but could have access to the facility if needed. They would also maintain an association with one of IMSI's Discipline Teams to ensure consistency with ongoing studies. These researchers could work on either contained samples that are delivered within, and never leave, a transportable containment vessel and/or uncontained samples that do not carry the same safety requirements. Requirements for receiving contained and uncontained samples would be very different, with shipping, transport, and sterilisation policies clearly defined in the Planetary Protection Protocol (see Section 2.5.3). For instance, permission for a given laboratory to receive contained samples could be contingent on a safety certification.

Maximising Science Return

As the guiding philosophy of IMSI is to maximize scientific return from samples, the best ideas for research, regardless of their source, should be pursued. In addition to the research funding programs outlined above, some mechanism should exist to involve scientists who have limited access to external funding or are based in countries that are not participants in the MSR campaign. The nature of such a mechanism is not yet determined. It could be funded as part of an overhead fee charged to participating countries and/or researchers, and it could be facilitated by having the researcher sponsored by (i.e., added to the research team of) an existing investigator.

4.2.2 Preliminary Sample Examination

Reliance on Planetary Protection Protocols

Initial analyses carried out in the SRF will need to follow still-TBD peer-reviewed protocols (Kminek et al., 2014). As noted in Section 2.5.3, the nature of work that will need to be carried out in the SRF (or off site but still within containment) prior to any general sample release to the broader scientific community cannot be fully detailed until planetary protection protocols for returned Mars samples are in place.

The SRF will require extensive analytical capabilities, including capability to provide basic characterization of samples (e.g., X-ray tomographic imaging within sample sleeves, photography, mass measurements, labelling, etc.). Determining the full scope of preliminary sample examination is beyond the scope of this study.

To reiterate, initial sample analyses must satisfy both planetary protection and science needs. Required measurements will be largely complementary and inform each other. High-quality planetary protection studies will be a necessary but insufficient evaluation of the samples, and preliminary analyses must also contribute to top-priority science objectives, such as those delineated by the E2E-iSAG (McLennan et al., 2012).

Examination Flow

After the sample canister has safely arrived on Earth, steps must be taken to document and archive all of the materials returning from Mars, including spacecraft and collected samples. Building upon the analysis flow suggested by Kminek et al. (2014), Figure 4-8 outlines a high-level approach by which materials could be handled, investigated, and stored.

Figure 4-9 provides additional details of the preliminary examination process. The focus is on the decision-making process rather than the definition of analyses to be conducted. The iMARS WG is not recommending what specific tests will be required to pass through each decisional gate. This process should be consistent with planetary protection protocols, which should build upon Rummel et al. (2002) to define criteria upon which decisions will be made to proceed from one step to the next.

Scientific, safety, and curatorial concerns will all play a major role during preliminary examination. Generally, science-led activities will comprise sample prioritisation; curation-led activities will consist mainly of the physical movement, tracking and storage of the materials; and safety considerations will be the primary criteria by which decisions are made to proceed to the next step. All data produced in this process will be collated in a preliminary-examination data catalogue. This catalogue will be made available to the public and will likely serve as the basis for the first external proposals to work with the samples. The highest data standards must be applied at the earliest stages of investigation.

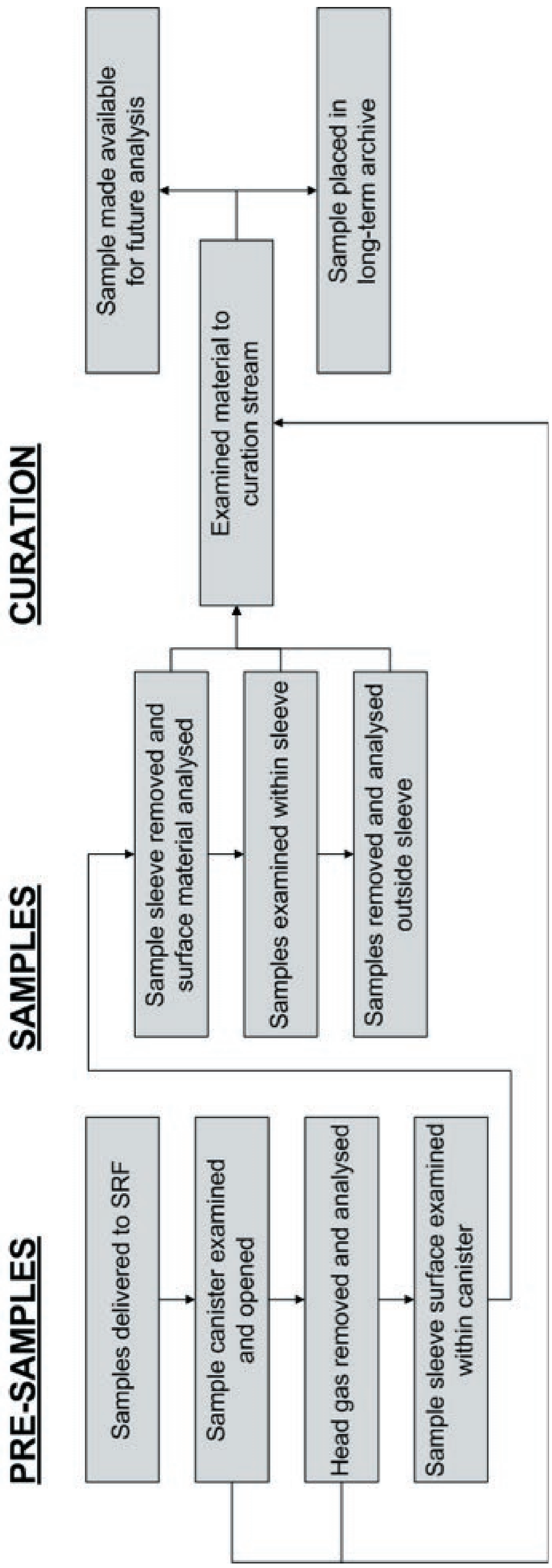
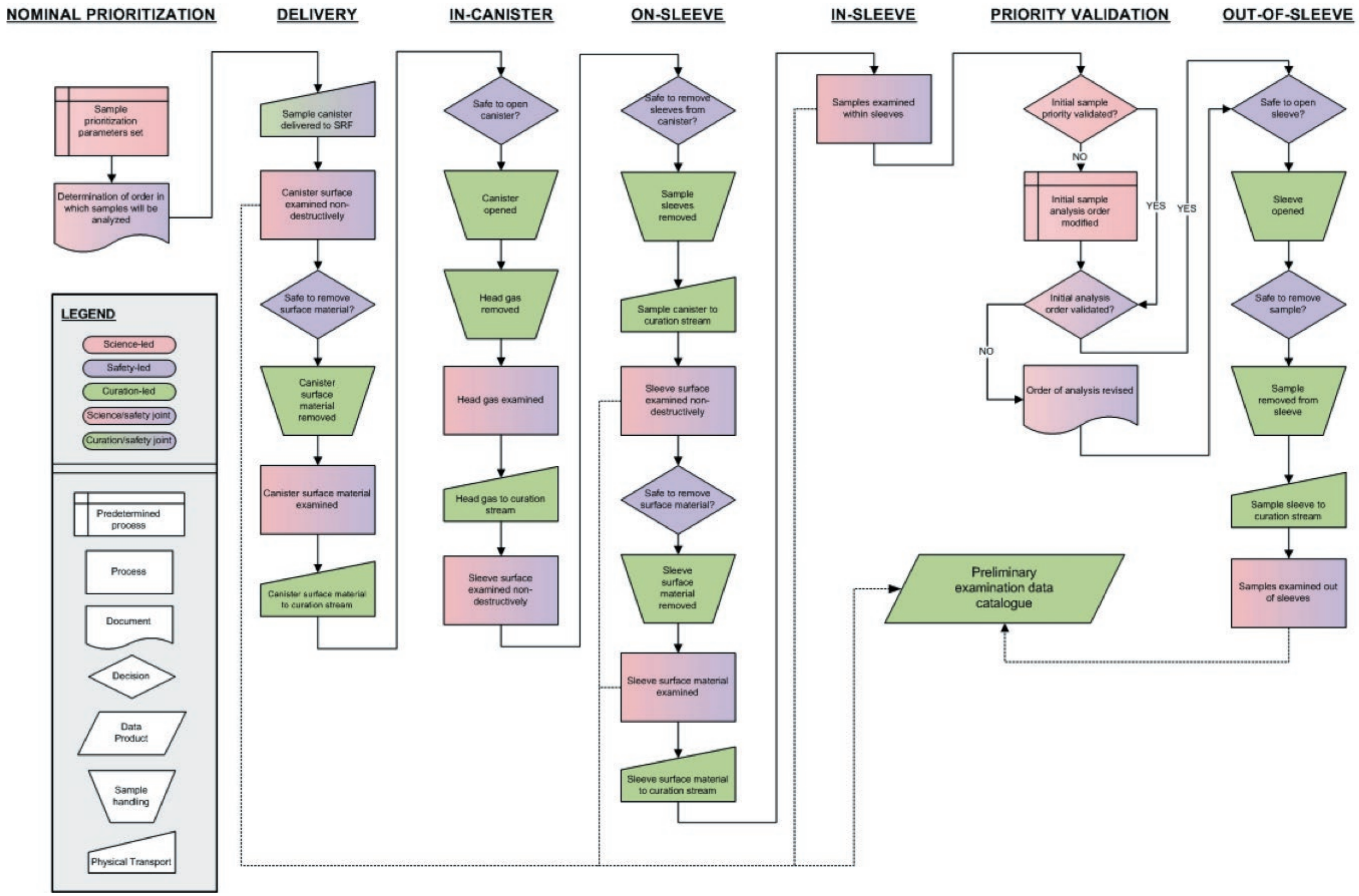


FIGURE 4-8: Proposed examination and archiving steps for returned materials

FIGURE 4 -9: Detailed decision flow during preliminary examination of samples



Additional Considerations

The initial examination of Mars samples will draw the attention of the world in a way not seen since Apollo 11 returned the first lunar samples. One lesson from the preliminary examination of Apollo 11 and 12 samples is that there is intense pressure to obtain results quickly, and fatigue within science teams and technical staff is likely to be an issue. One member of the Lunar Sample Preliminary Examination Team (LSPET) described being in a "daze of exhaustion" after three weeks of analysing Apollo 11 samples (Taylor, 1994). In a BSL-4 setting, fatigue could further lead to breaches in protocol that could undermine public confidence. Accordingly, considerable attention should be paid to developing plans for mitigating fatigue issues – for example, by having extensive training and a program of rotating staff, especially during the first few weeks to months after sample return.

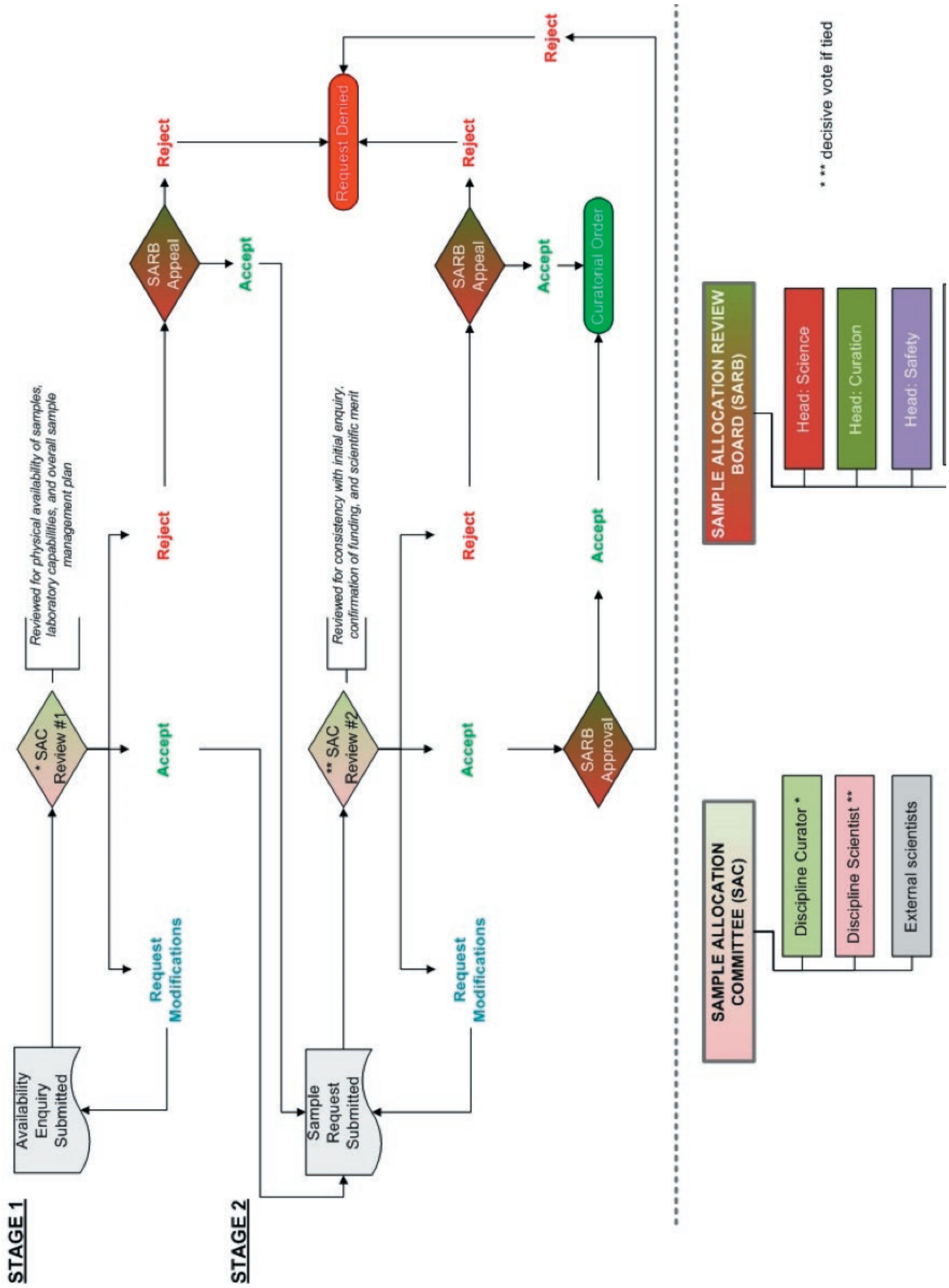
4.2.3 Sample Access and Allocation

Guiding Principles and Approach

In addition to scientists working within the SRF, external investigators from a broad array of disciplines will also look to obtain both contained and released samples. Many stakeholders will have an interest in displaying samples and/or using them for instructional purposes. Moreover, Mars samples would have enormous value on any black market, warranting great care in ensuring the security of samples. The importance of a well-designed and closely managed sample allocation and access structure cannot be overstated, though it should be reiterated that developing and executing the necessary security precautions must not preclude samples from being released in a timely manner.

To ensure that Mars samples are allocated to the most deserving scientists carrying out the highest quality research and that the allocation process is fair and transparent, the iMARS WG recommends a two-stage, two-tier allocation structure (Figure 4-10). Described in further detail below, this structure is designed to deal with uncontained samples and contained samples that might be transported to external laboratories. Allocation procedures should be reviewed and updated as circumstances warrant.

FIGURE 4-10: The proposed two stage, two tiered sample allocation process



Review Panels

Under this model, Sample Allocation Committees (SACs) would be the primary interface between scientists interested in working with Mars samples and the samples themselves. SACs would be assigned to each of the major sample suites (e.g., SAC-Ign dealing with igneous suites; SAC-Sed dealing with sedimentary suites, etc.). These committees should including the respective Discipline Curator and Discipline Scientist along with rotating external scientists. The purpose of the SACs would be to determine sample availability for proposed investigations and approve formal sample requests (see below).

Serving as an oversight body for the SACs, a Sample Allocation Review Board (SARB) would include the Heads: Science, Safety, and Curation (or their delegates) and rotating external senior scientists. The Director could participate in an ex-officio role. The SARB would finalize SAC approvals of sample requests, decide on appeals of SAC decisions, and rule on any special requests (e.g., for archival material, museum or other displays and other educational purposes). For special requests (but not for appeals), the SARB should seek input from the appropriate SAC.

Stage 1: Sample Availability Enquiry

Stage 1 of the review of a sample request would constitute a determination of sample availability. If a given request were to cross the expertise of more than one SAC, then the most appropriate SAC could be designated to lead an ad hoc committee made up of selected members of other relevant SACs. Requests would be reviewed with a focus on physical availability, addressing such topics as:

- General availability: Does the sample exist? Is it being used by someone else?
- Laboratory verification and validation: Can the laboratory make the proposed measurements?
- Sample management plan: How long will the sample be needed? Will the sample be kept safe? Will the analyses be destructive or non-destructive? What materials are expected to be returned?
- Consistency with the sampling strategies: Are the proposed investigations aligned with published suite-specific strategies? If not, is an appropriate justification provided?

After review, the SAC could determine that the sample is in principle available, request additional information before making a decision, or determine that the sample is not available. Negative decisions could be appealed to the SARB. In case of a tied vote, the Discipline Curator's vote would be decisive. However, if the Discipline Scientist were to hold that a decision is at odds with the best scientific use of samples or with standard practices, s/he should be empowered to appeal to the SARB.

Stage 1 determinations would include a "good faith effort" by the IMSI to ensure that the requested samples would remain available for some reasonable amount of time (likely on the order of 6-12 months). The intent to do so would not be binding, but requesters should be informed of any change in availability in a timely fashion.

Stage 2: Formal Sample Request

Requesters who have met Stage 1 requirements would then be required to submit a formal request for Stage 2 review. Formal requests must show that researchers have funding and facilities in place (or reasonably committed) and have submitted their research proposal to peer review, typically by one or more of their national science funding agencies. Stage 2 SAC review would focus on:

- Consistency with the initial enquiry: Are the requested samples appropriate and valid for the proposed investigations?
- Changed circumstances: Is the researcher still capable of performing the proposed investigations?
- Validity of funding, facilities and peer review process: Has the scientific merit of the proposed research been reviewed by a suitable body? Has sufficient financial support been committed?

If a formal request is consistent with the initial request and the proposed research is funded, then samples should be made available. As with Stage 1 review, the SAC in Stage 2 may approve the request; ask for additional information before making a decision, or turn down the request. Approved requests would go to the SARB for final concurrence. Communications between SACs and the SARB should be ongoing, and final SARB approval should be pro forma. A negative SAC decision would be subject to appeal to the SARB. In the rare case of a tie, the Head: Science would hold the deciding vote. Once a sample is formally allocated, the researchers who requested it would establish a loan agreement with the SRF Curatorial Office, and the sample would be shipped.

Proposals from Research Consortia

The iMARS WG contends that the greatest science return from Mars samples will be accomplished by well-coordinated studies that maximize the usage of a given allotment of a sample, while minimising sample disruption and consumption. While sample requests from any scientist with a good idea should be considered, proposals from science consortia that would carry out multiple coordinated studies on individual sample aliquots should be encouraged.

> *Finding: Well-coordinated proposals from consortia within the scientific community should be encouraged to ensure the most efficient use of samples.*

4.2.4 Data Rights and Distribution

Data Considerations

Two key issues for any planetary mission are how and when the wider scientific community gains access to mission data, and how these needs are balanced against the needs of mission scientists to publish results based on these data. For a Mars sample return campaign, another issue is rights to and distribution of data collected within the SRF, for preliminary characterization and for planetary protection. Finally, although peer-reviewed publication is the best way for data collected by Guest Scientists and External Investigators to be made available to the wider scientific community, the reality is that not all research results are published in a timely manner. Thus, some mechanism for ensuring the timely distribution of results will also be needed.

Data obtained from returned Mars samples will likely fall into four basic categories, each requiring different rules relating to data rights and distribution:

- Pre-sample-return data: data collected by elements of the MSR campaign (e.g., caching rover, fetch rover/MAV, sample return orbiter);
- Preliminary sample examination phases (by MSPET): measurements made for basic characterization and planetary protection purposes;
- Data obtained by Guest Scientists and External Investigators: measurements on samples that have been made available through the sample allocation process; and
- Secondary data: information resulting from interpretation of primary data.
- Recommendations for each category are described below.

Pre-Return Data

Planetary exploration has a long history of rapid dissemination of mission data to the public. Data release venues include the ESA Planetary Science Archive (www.rssd.int) and the NASA Planetary Data System (http://pds.nasa.gov/). Additional compilation archives, such as the Analyst's Notebook (http://an.rsl.wustl.edu/), may be more accessible to scientists less familiar with planetary mission archival systems.

The iMARS WG contends that all data collected during the course of the MSR campaign should be treated like any other mission data, with data release taking place in a timely fashion through appropriate data release system(s) to be determined by partners in the MSR campaign.

The WG further recommends that all MSR campaign mission data be made available in a common format, preferably at a common web interface – a "one-stop shop" for data. The system should be as user-friendly as possible to encourage participation by scientists who may have little previous experience working with planetary science data archives. Implementing this recommendation may require considerable developmental work and international cooperation if more than one archival system is employed.

Preliminary Examination Phase

Once samples have been delivered to the SRF, the MSPET will conduct observations and measurements for basic science characterization and planetary protection. The results of these analyses will be crucial for determining subsequent research paths.

Achieving a balance between the goal of rapid data dissemination and the need for a proprietary period for the MSPET will be challenging. Familiarity with the data sets will likely be one evaluation criterion for sample requests, and thus the scientific community will be pushing for as rapid a release of data as possible. However, MSPET scientists should also be able to work with their preliminary data prior to release. The iMARS WG recommends an MSPET proprietary data period on the order of several months to a year. Once that period has passed, data should be released in a readily accessible venue.

A good model for data release is the Scientific Earth Drilling Information Service (SEDIS, http://sedis.iodp.org/) or the earlier Janus database of the ocean drilling programs (http://web.iodp.tamu.edu/JanusReportOverview/faces/ExpeditionOverview.xhtml). In these cases, a proprietary period for data collected onboard drilling ships lasts for one year after the ship returns to port. For MSR, we suggest that IMSI should set up a high-security IODP-like web site where MSPET data are archived in a two-tier system. A Pre-Data Release Access Section (i.e., prior to public release of data) would be password-protected for SRF MSPET personnel and, where appropriate, for Guest Scientists. Once the proprietary period has passed, all data would then be placed onto a public Post-Data Release Access Section of the website.

External Research Data

External data are the data produced by Guest Scientists, External Investigators, and their research teams. These researchers would have to provide acceptable data management and archiving plans in their research proposals, analogous to proposals for planetary mission involvement that generate data. While individual funding agencies may have their own requirements, we propose that ISMI restrictions on externally funded scientists should be limited.

External researchers should be provided a generous period of time to complete and publish their work (TBD, but likely measured in years). At some point in time, though, their data would be made available on the IMSI website. To avoid disputes, the iMARS WG recommends that formal sample allocation agreements include appropriate language.

Some measure of flexibility will be needed in data-release policy. As an example, researchers might request an extension of a proprietary period to accommodate graduate students or post-docs who are working on samples or other circumstances such as broken equipment, relocation, or illness. Researchers who fail to publish results and/or make their data available could be at a disadvantage in reviews of future sample allocation requests, with repeat offenses perhaps leading to a ban on sample access.

"Secondary" Data

IMSI will have the capability to catalogue and distribute primary data collected on Mars samples by ensuring that researchers make such data available as part of their sample allocation agreements. IMSI will also control data returned by the elements of the MSR campaign. However, once data are publicly released, it will be extremely difficult to monitor secondary data produced by further analyses. Accordingly, the data distribution system should focus on primary data obtained by MSR missions and directly from measurements of samples.

> *Finding: Data should be made publicly available in readily accessible formats as soon as feasible at each stage of analysis.*

4.3 Curation Plan

4.3.1 Sample Tracking and Routing

Curatorial Approach

The distribution and tracking of samples within and outside the SRF should satisfy, as a minimum, the following criteria:

- Adherence to planetary protection protocols and local, national and international regulations on transport/movement of biohazardous materials in close collaboration with the Safety Branch;
- Maximisation of science return by ensuring the maintenance of a thorough documentation trail during investigations (within or outside of the SRF) to allow for re-use of samples when possible;
- Prevention of cross-contamination of samples, including cross-contamination between sterilized and non-sterilized samples and contamination between different sample types and/or samples from different acquisition events (i.e., individual Mars locations with differing geologies, separate Mars missions); and
- Assurance that external laboratories maintain sample handling and curatorial protocols, e.g., cleanliness, sub-sampling, documentation.

Although the safety aspects of MSR add a level of complexity to sample distribution, experience with existing extraterrestrial sample collections and sensitive biological materials offers a solid foundation for developing MSR protocols.

Tracking and Routing Procedures

Robust procedures for the curation and distribution of extraterrestrial materials to scientists around the world have been in existence since the Apollo lunar missions (Allen et al., 2011). Over time, these curatorial procedures have been updated based on experience working with different types of materials from a variety of sample return missions, including Genesis solar wind samples (Allton et al., 2006), Stardust cometary dust samples (Zolensky et al., 2008), and Hayabusa asteroid surface samples (Yada et al., 2014). Experience has also been gained with meteorite samples, especially those recovered from Antarctica or those witnessed to fall and rapidly recovered (McCall et al., 2006; Righter et al., 2014). Thus MSR campaign planners have a wealth of information to draw on in developing curatorial procedures for Mars samples.

Figure 4-11 shows a proposed IMSI sample distribution plan. Upon receiving a Curatorial Order from the

SARB, IMSI would prepare required samples for analysis. Some analyses would be carried out within the SRF whereas others would be carried out in external laboratories.

Whether samples are analysed within or outside the SRF, it is imperative that samples returned for curation on completion of analyses are managed in the same way they were before allocation for analysis. To this end, investigators must record a thorough documented history of the samples whilst they are in their possession, including any sub-sampling or preparation, and they may be subject to audits. NASA has used this methodology for the return of Apollo samples by external investigators (Form F-75, "Return Sample Accountability and History," http://curator.jsc.nasa.gov/lunar/sampreq/requestdates.cfm), and JAXA has used it for Hayabusa samples (http://hayabusaao.isas.jaxa.jp/3rd/docs/accepted.html).

Samples returned after analysis will need to be examined for any evidence of damage, such as unexplained mass loss or obvious signs of contamination. If the samples are in order, they will be returned to one of two vaults depending on whether they require containment. These vaults will be only for samples returned after analysis to avoid potential contamination of pristine materials. If the samples remain suitable for further studies, they will be made available under the SAC and SARB process. Samples returned and deemed not suitable for reuse will be curated to the same high standards as all other samples. Advances in analytical instrumentation and techniques could render such samples usable for future research.

Cleanliness and Contamination Considerations

The ever-increasing challenges posed by the development of new analytical techniques and instrumentation, where even a tiny amount of terrestrial organic or inorganic contamination could hinder or prevent successful analysis, have already influenced present-day curation of extraterrestrial materials. Many curation laboratories utilise high-level clean environments (e.g., ISO 4 or better) to store, handle and prepare samples prior to distribution for scientific investigations (Allen et al., 2011; Yada et al., 2014.)

As part of the sample allocation review process, external investigators will be required to prove that they have the infrastructure and experience required to work with materials in a clean environment with regular monitoring for potential contamination. Laboratories receiving samples must be capable of maintaining the same levels of cleanliness as the SRF. This requirement is particularly critical for investigations in which samples or materials prepared from them (e.g. mounted stubs, grain separates) are to be used for a consortium investigation or where samples can be re-used for a different study. Investigators will likely have to use certified clean laboratories and/or work areas, externally verified and validated cleaning techniques, and witness plates. Any issues that arise during studies, such as contamination on witness plates, would need to be reported immediately to the Head: Science and Head: Curation, so they could be documented and mitigating actions taken if necessary.

> *Finding: The development of procedures for sample tracking and routing should be leveraged from existing protocols (e.g., Apollo, Stardust, Hayabus, OSIRIS-REx).*

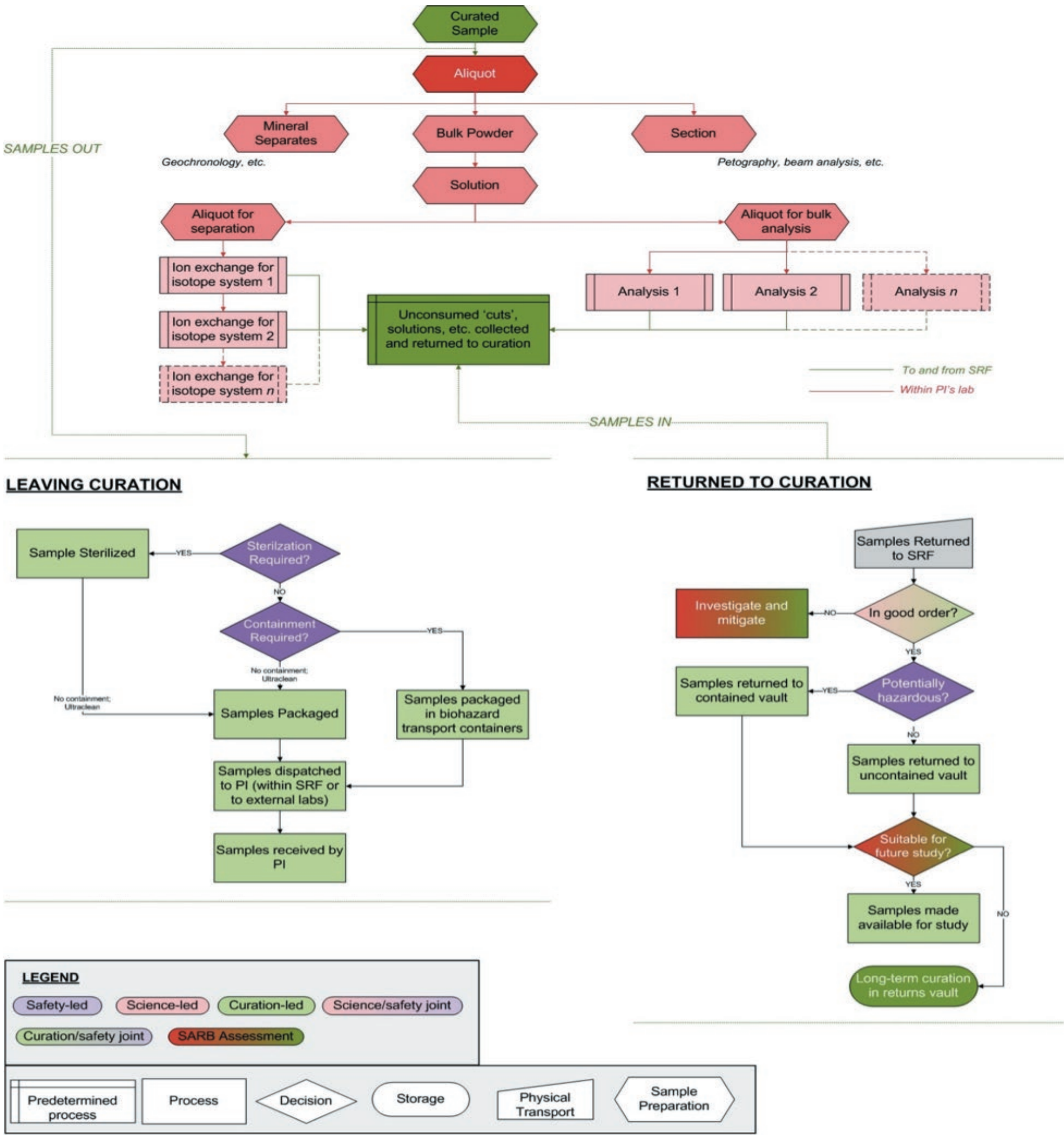


FIGURE 4 -11: Proposed IMSI sample distribution and tracking plan

Containment Considerations

To comply with planetary protection requirements, samples will need to remain in containment until such time as they are proven to be non-hazardous. To satisfy this requirement, samples will need to be analysed in BSL-4 level (or superior) containment laboratories and transported to and from those laboratories in BSL-4 rated transport containers. Alternatively, to be certified to leave containment, samples will need to be sterilised, using a verified technique (see Section 4.3.2).

4.3.2 Sterilisation of Subsets

Issues surrounding sample sterilisation have been addressed in previous Mars Sample Return studies (National Research Council, 1997; Committee on Planetary and Lunar Exploration, 2002; Rummel et al., 2002; NRC, 2009). The ability to sterilise Mars samples will be critical to the function of the SRF, and to the MSR campaign itself. The two most effective sterilisation methods identified for Mars samples are dry heat and gamma radiation, alone or in combination, with the caveat that high temperatures required for dry heat sterilisation will be detrimental to many scientific investigations (Committee on Planetary and Lunar Exploration, 2002).

While the effects of gamma radiation on geological materials have been explored (Allen et al., 1999) further work on the effects of dry heat and/or gamma irradiation sterilisation is required to prepare for MSR. The National Research Council's (NRC/s) Quarantine and Certification of Martian Samples report recommends that:

> *"A program of research should be initiated to determine the effects on organic compounds in rocky matrices, and also on microscopic morphological evidence of life, of varying degrees of application of heat and gamma irradiation. This research should be started well in advance of the return of the Mars samples, so that treatment protocols can be designed intelligently and data obtained from analyses of treated samples can be interpreted with minimal ambiguity" (Committee on Planetary and Lunar Exploration, 2002, p. 40).*

Whilst method(s) to be used for Mars sample sterilisation are still uncertain, the question of which and how much sample(s) should be sterilised remains open. Unless samples are proven to be non-hazardous, they will have to be sterilised before they are certified to leave containment. While this approach mitigates the "stuck in containment" scenario, it also raises many issues. What if subsequent analysis indicates that a sterilised sample originally contained organic molecules constituting a biomarker signal, or some other significant organic signature such as abiotically produced organic molecules? What if it was discovered that martian life had been destroyed? Despite so much previous work, these questions and issues remain open.

The SCR mission should have a scientific payload capable of providing a sufficient level of geological contextual information, e.g., detection of organic carbon and different organic molecules. Thus, informed decisions on sample sterilisation could be made during sample acquisition. For instance, samples with scientifically interesting organic inventories would require detailed investigations whilst in containment, prior to any decision on sterilisation and wider release. The iMARS WG supports and resubmits the NRC's recommendation (Committee on Planetary and Lunar Exploration, 2002) that further work on sterilisation methods be a crucial part of MSR planning. Studies to identify specific sterilisation techniques and their effects on geological samples should be prioritised in the near term.

> *Finding: Additional research must be conducted on the methods and doses required to adequately sterilise samples returned from Mars, including a definition of the effects of these techniques on geological samples.*

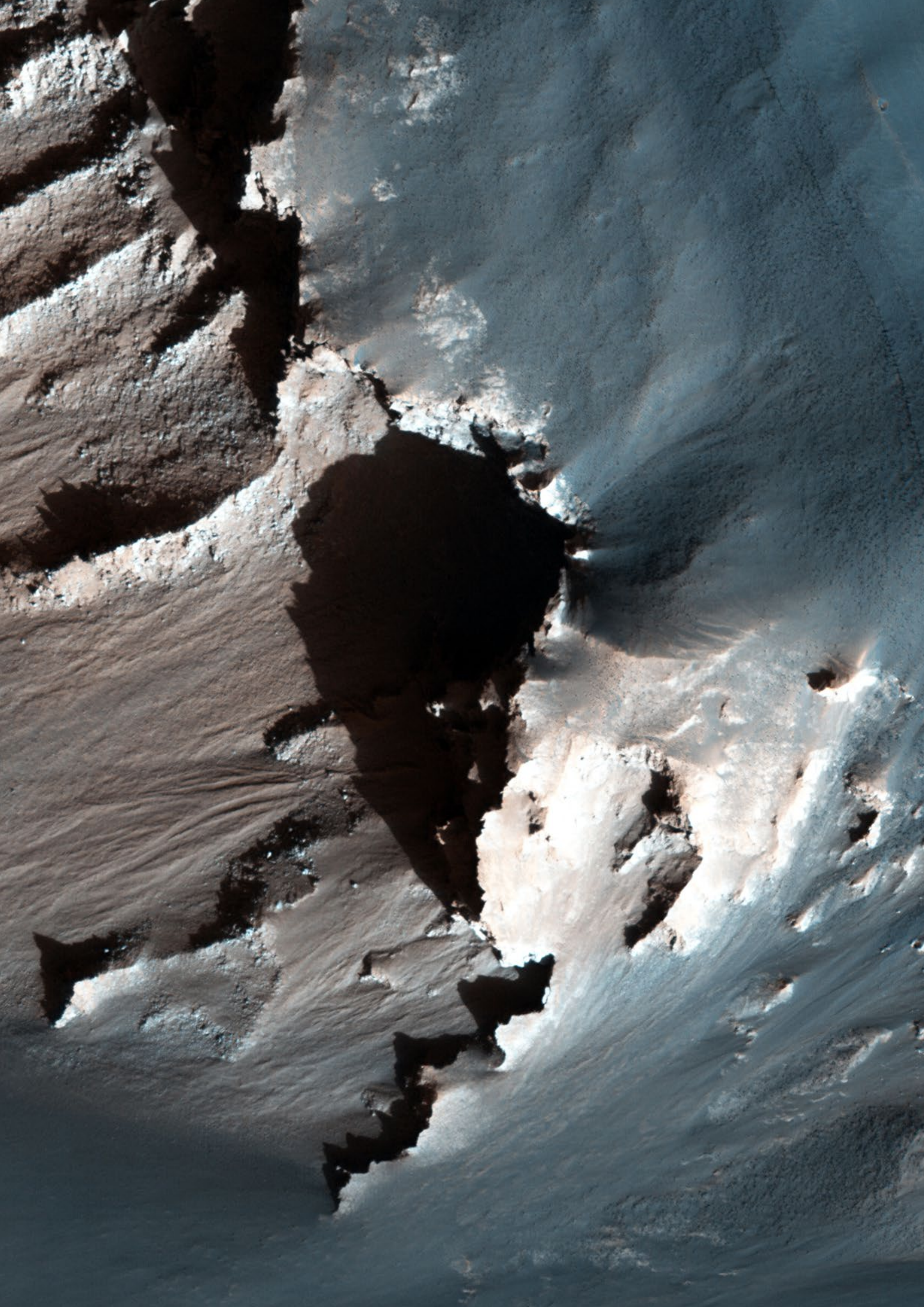
4.3.3 Preservation for Future Analyses

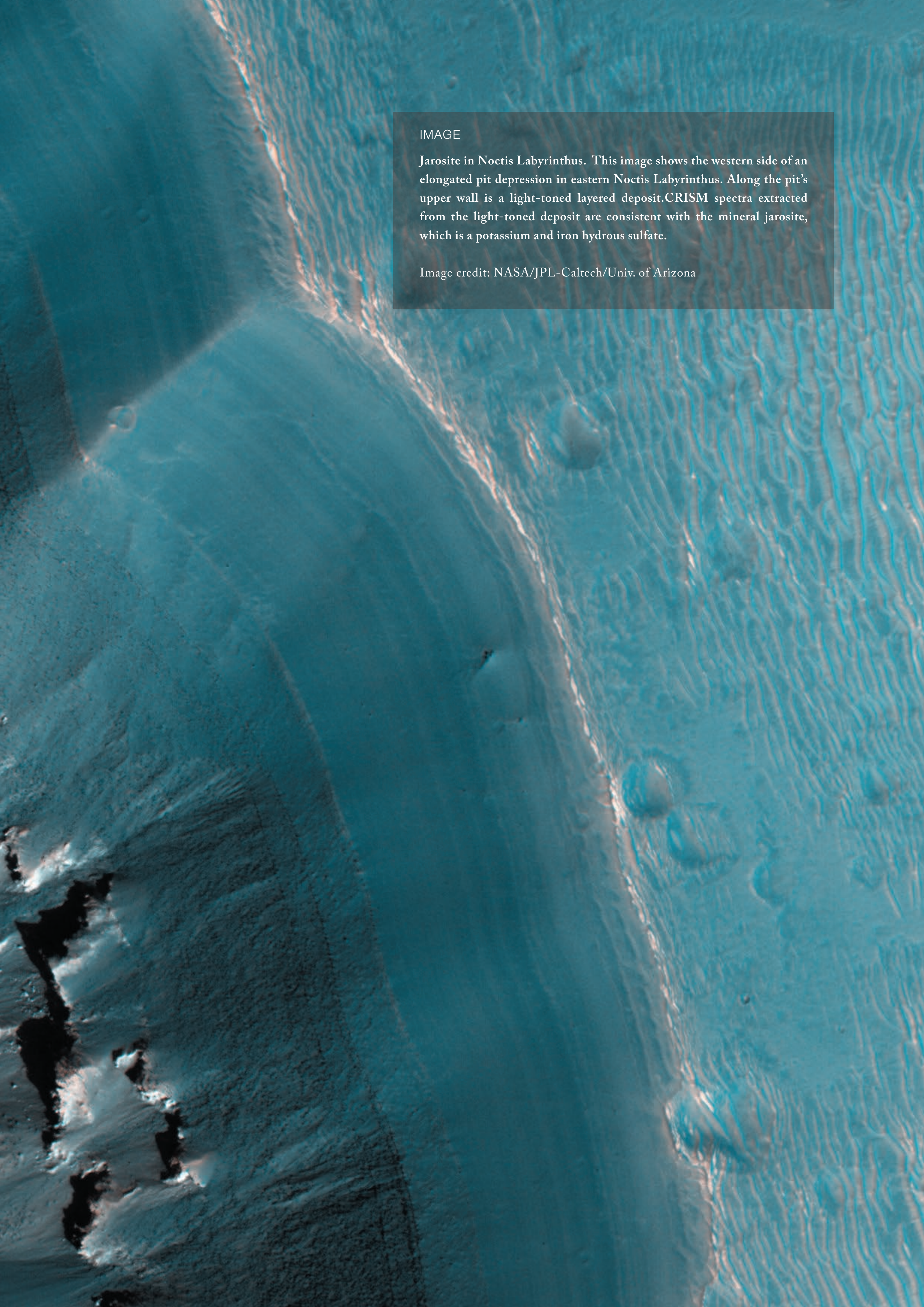
The first samples returned from Mars will be some of the most precious and scientifically sought after samples in history. Samples will be studied using the full array of cutting-edge analytical equipment in world-leading laboratories. Mars sample science will be truly a global effort. However, sample mass will be limited, on the order of about 15 grams per sample and a total mass of about 500 grams (McLennan et al., 2012). Even a smaller amount will be made available for immediate analysis. With new analytical techniques constantly developed, refined, and improved over time, an important curatorial requirement will be to preserve a portion of pristine returned samples for future analyses.

However, determining the amount of sample to be set aside remains a challenge. On the basis of information gathered from curators of existing extraterrestrial sample collections and other experts, McLennan et al. (2012) recommended that 40% by mass of each sample should be reserved for future analysis. However, if particularly exciting results such as detection of life are obtained during the mission or preliminary examination, then priorities for sample allocation and use will dramatically change (as noted in Section 2.5.1). Specific recommendations for action in the event of life detection are beyond the scope of this report.

Following McLennan et al. (2012), we propose that preserving 40% by mass of each sample for future science remains a valid recommendation to use as a starting value. However, we recommend that this value be revisited at different stages of the MSR campaign: during Mars surface operations (investigation of specific sites of interest and sample acquisition); during Preliminary Examination in the SRF for planetary protection and scientific purposes; and at the end of the first scientific investigation phase (e.g. about one year after return). Another possibility is to select a portion of pristine samples to be preserved immediately. In this case, a TBD number of individual sample containers would remain unopened on return and investigated only via techniques such as CT scanning, which do not require removal of samples from containment. Determining whether this is a valid approach would depend on the results of Mars surface operations and sample selection/acquisition. If blank samples are collected on Mars, we recommend that at least one of these blanks be left in a pristine, unopened state upon return to Earth. These pristine blank samples will be of great value should any results be questioned in regards to possible contamination and false-positive results, during planetary protection investigations in particular.

> *Finding: A portion of the returned samples, nominally 40%, should be stored at a location other than the primary SRF, with at least one of the "blanks" left in a pristine, unopened state.*



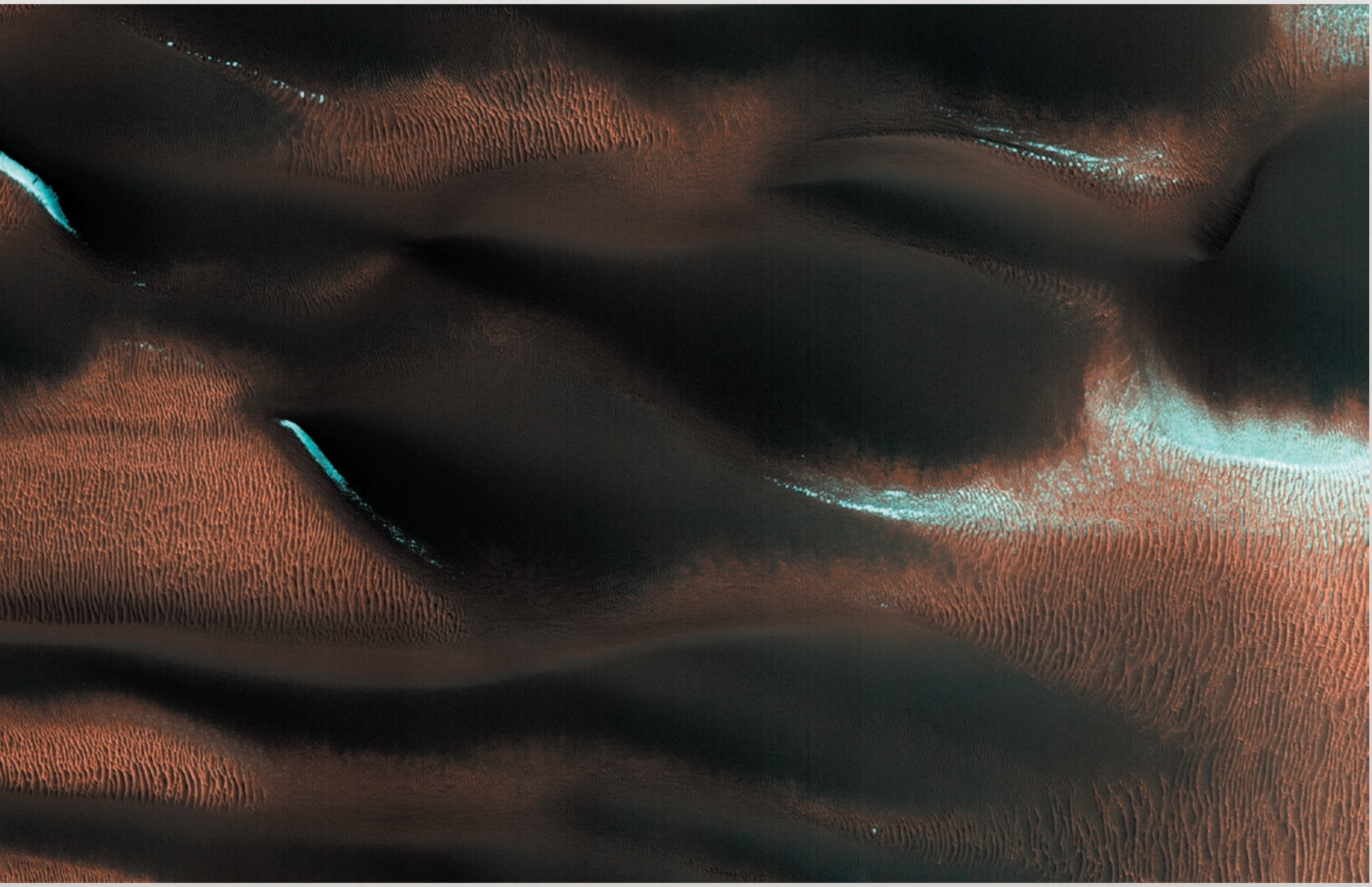


IMAGE

Jarosite in Noctis Labyrinthus. **This image shows the western side of an elongated pit depression in eastern Noctis Labyrinthus. Along the pit's upper wall is a light-toned layered deposit.CRISM spectra extracted from the light-toned deposit are consistent with the mineral jarosite, which is a potassium and iron hydrous sulfate.**

Image credit: NASA/JPL-Caltech/Univ. of Arizona

V. | Conclusions and Recommendations



ABOVE IMAGE

Aeolian Features of Scandia Cavi. This HiRISE image shows modified barchan dunes with shapes that resemble "raptor claws." This locality is in the Northern Lowlands directly east of Dokka Crater in Scandia Cavi.

Image credit: NASA/JPL-Caltech/Univ. of Arizona

In this report the iMARS WG has proposed an MSR campaign architecture that could safely return samples from Mars in 2031/33, along with a follow-on sample management plan to ensure proper utilisation of returned samples. The proposed MSR campaign, built upon previous efforts, provides updates of architectural, technological, scientific and programmatic details. This MSR campaign, if implemented, could take advantage of samples collected by the Mars 2020 mission. Progress toward the goal of MSR will require the international community to work together, with near-term work required on critical issues identified in this report.

5.1 Conclusions

As a result of its Phase 2 work, the iMARS WG has reached the following conclusions:

- Programmatics:
    - MSR is a complex campaign that will depend on international cooperation. Campaign implementation and management will require well defined interfaces and agreements on standards and regulations.
    - The dialogue on the distribution of responsibilities for delivering different MSR elements needs to mature, involving executives of all interested organisations. A successful partnership will depend on long-term commitments of participating organisations. Early and binding agreements will be necessary for success.
    - Several missions have advanced our understanding of Mars since 2008 and validated key new technologies applicable to MSR. Samples from Mars could be returned in 2031/33 under the iMARS WG Phase 2 proposed architecture and sample management plan.
- Technology:
    - The development timeline for the Sample Return Facility is comparable to those for flight elements (10+ years from inception to operational readiness).
    - Campaign robustness should be addressed as early as possible. Our reference architecture (3+1) provides flexibility in responsibilities, schedule management, and technical failure mitigation. It also allows for multiple

entities to participate in technical implementation.

- MSR technology requirements are understood and within reach. A strong technology development effort is under way by several agencies. Two technologies that are critical and specific to the MSR campaign are the Mars Ascent Vehicle and bio-sealing and "break-the-chain" methods. Development of these technologies is already under way.

- An end-to-end MRSH plan outlining sample recovery, transport, and delivery procedures must be produced.

- Sample management:

    - Major advances have been made in the formulation of a Sample Science Management Plan, including a proposed structure and an implementation approach.

    - Scientific, safety and curatorial aspects of sample management must be integrated in the development of a sample management structure.

    - While progress has been made understanding MSR planetary protection implications and associated technology developments, key requirements and protocols require further development, in particular for the Sample Receiving Facility.

5.2 Recommendations

Following from these conclusions, the iMARS WG makes the following recommendations:

Programmatics:

- An international MSR Science Institute (IMSI) should be established as part of the governance scheme for this endeavour. In developing this Institute, input should be sought from the IODP (Section 2.7).

- It is necessary to define a flexible and adaptable model for cooperation and a coordinated decision making process that encourages long-term commitments by participating organisations and demonstrates clear benefits to them. The model should allow partners to contribute in line with their respective priorities and budgets (Section 3.4.1).

- For SRF management and operations and science participation, dedicated programmatic working groups should be created to define cooperation models and guidelines for the application of standards (Section 3.4.1).

- Interested nations should sign a declaration as soon as possible to allow further development of an MSR architecture and governance scheme (Section 3.4.1).

- Because public support will be desirable for MSR flight missions and crucial for SRF development, the MSR campaign will require a formal public engagement strategy (Section 4.1.2).

- Detailed implementation plans should be put in place as soon as possible because of the projected timeline for designing, constructing, and operating a Sample Return Facility. As part of the plan, minimum requirements for safely receiving the samples on Earth should be clearly defined (Section 4.1.4).

- Participation in IMSI decision making bodies should be proportional to mission element contributions (Section 4.1.5).

Technology:

- A "3+1" architecture, consisting of three flight missions and at least one ground-based SRF, is recommended to implement MSR (Section 3.1.1).

- The Mars Ascent Vehicle and the functions of bio-sealing and "break-the-chain" have been identified as the most critical areas in MSR campaign. These two areas need to be further explored and solutions closely monitored until the validation process is complete (Section 3.2.1).

- Technology development efforts should be coordinated among participating organisations (Section 3.2.1).

- Future studies will be needed to clearly define sample lifetime issues (Section 3.1.1).

Sample Management:

- A Planetary Protection Protocol should be produced as soon as it is feasible by an international working group under the authority of COSPAR or other international body (Section 2.5.3).

- The IMSI science, safety, and curatorial management should be collocated at the SRF, while the implementation of executive level and virtual science teams can be internationally distributed (Section 4.1.1).

- The organisation of the science teams, sample allocation, and test protocol development should be specific to each sample suite returned by the mission (Section 4.1.2).

- Scientific access to samples should be driven by scientific excellence, independent of the financial contributions of the bidder's home country (Section 4.1.5).

- Sample science, planetary protection, and curatorial expertise should inform the sample collection mission development (Section 4.2.1).

- Well-coordinated proposals from consortia within the scientific community should be encouraged to ensure the most efficient use of samples (Section 4.2.3).

- Data should be made publicly available in readily accessible formats as soon as feasible at each stage of analysis (Section 4.2.4).

- The development of procedures for sample tracking and routing should be leveraged from existing protocols (e.g., Apollo, Stardust, Hayabusa, OSIRIS-REx) (Section 4.3.1).

- Additional research must be conducted on the methods and doses required to adequately sterilise samples returned from Mars, including a definition of the effects of these techniques on geological samples (Section 4.3.2).

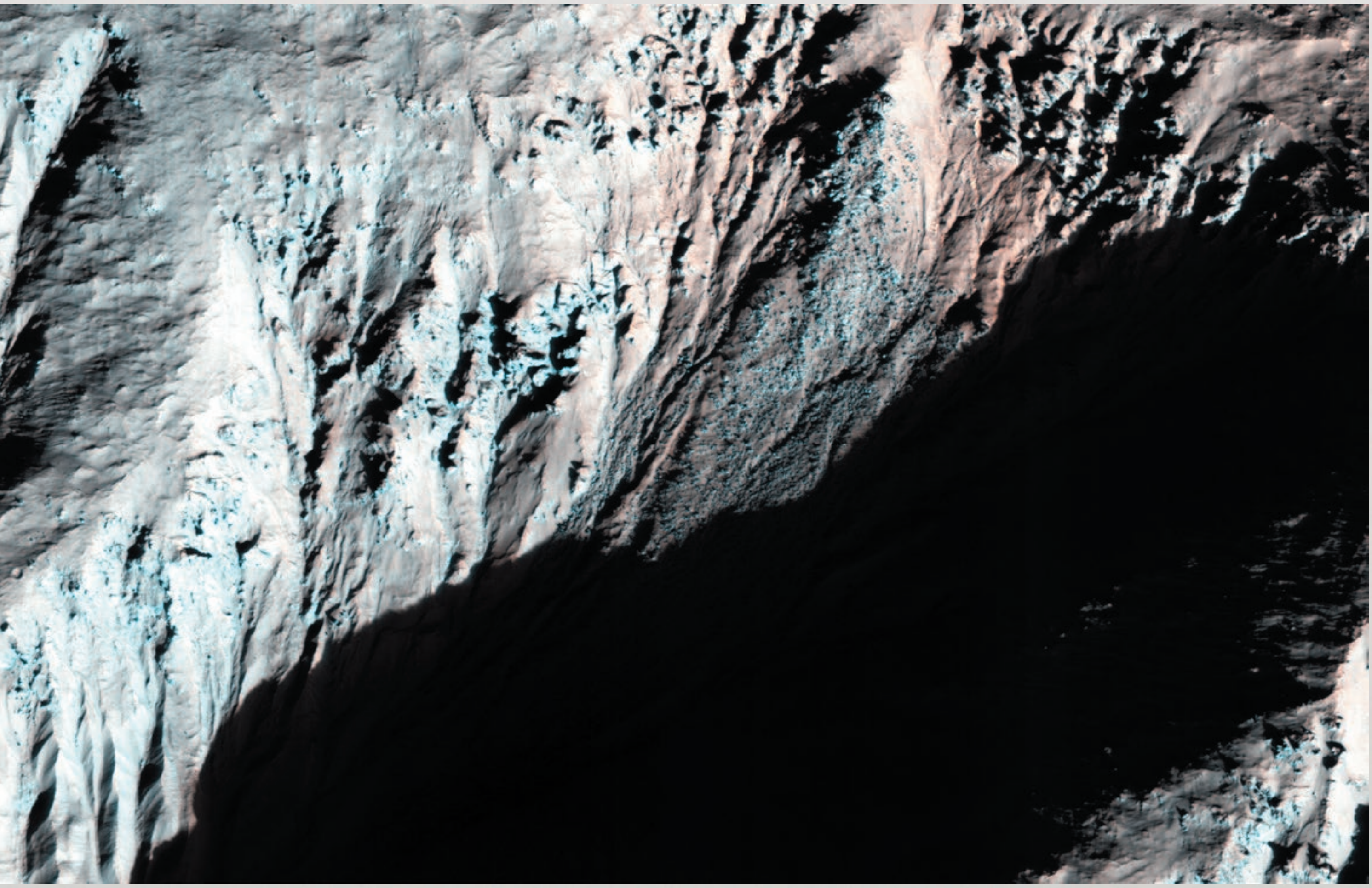
- A portion of the returned samples, nominally 40%, should be stored at a location other than the primary SRF, with at least one of the "blanks" left in a pristine, unopened state (Section 4.3.3).

IMAGE

The Nili Fossae region, located on the northwest rim of Isidis impact basin, is one of the most colorful regions of Mars. The colors over many regions of Mars are homogenized by the dust and regolith, but here the bedrock is very well exposed, except where there are sand dunes.

Image credit: NASA/JPL-Caltech/Univ. of Arizona

A. | Appendices



ABOVE IMAGE

This image was acquired to look for frost on these generally equator-facing slopes, which are visible in the shadows after enhancing the brightness levels. It is also a dramatic image given the low-sun illumination.

Image credit: NASA/JPL-Caltech/Univ. of Arizona

iMARS

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A.2 Summary of COSPAR Planetary Protection Levels

(Descriptions reproduced as presented at: http://planetaryprotection.nasa.gov/about-categories/) Category I includes any mission to a target body, which is not of direct interest for understanding the process of chemical evolution or the origin of life. No protection of such bodies is warranted and no planetary protection requirements are imposed.

Category II includes all types of missions to those target bodies where there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote chance that contamination carried by a spacecraft could jeopardize future exploration. The requirements are only for simple documentation. This documentation includes a short planetary protection plan is required for these missions, primarily to outline intended or potential impact targets; brief pre-launch and post-launch analyses detailing impact strategies; and a post-encounter and end-of-mission report providing the location of inadvertent impact, if such an event occurs.

Category III includes certain types of missions (typically a flyby or orbiter) to a target body of chemical evolution or origin-of-life interest, or for which scientific opinion holds that the mission would present a significant chance of contamination which could jeopardize future biological exploration. Requirements consist of documentation (more involved than that for Category II) and some implementing procedures, including trajectory biasing, the use of clean rooms (Class 100,000 or better) during spacecraft assembly and testing, and possibly bioburden reduction. Although no impact is generally intended for Category III missions, an inventory of bulk constituent organics is required if the probability of inadvertent impact is significant.

Category IV includes certain types of missions (typically an entry probe, lander or rover) to a target body of chemical evolution or origin-of-life interest, or for which scientific opinion holds that the mission would present a significant chance of contamination which could jeopardize future biological exploration. Requirements include rather detailed documentation (more involved than that for Category III), bioassays to enumerate the burden, a probability of contamination analysis, an inventory of the bulk constituent organics, and an increased number of implementing procedures. The latter may include trajectory biasing, the use of clean rooms (Class 100,000 or better) during spacecraft assembly and testing, bioload reduction, possible partial sterilization of the hardware having direct contact with the target body, and a bioshield for that hardware, and, in rare cases, a complete sterilization of the entire spacecraft. Subdivisions of Category IV (designated IVa, IVb, or IVc) address lander and rover missions to Mars (with or without life detection experiments), and missions landing or accessing regions on Mars which are of particularly high biological interest.

Category V pertains to all missions for which the spacecraft, or a spacecraft component, returns to Earth. The concern for these missions is the protection of the Earth from back contamination resulting from the return of extraterrestrial samples (usually soil and rocks). A subcategory called "Unrestricted Earth Return" is defined for solar system bodies deemed by scientific opinion to have no indigenous life forms. Missions in this subcategory have requirements on the outbound (Earth to target body) phase only, corresponding to the category of that phase (typically Category I or II).

For all other Category V missions, in a subcategory defined as "Restricted Earth Return", the highest degree of concern is expressed by requiring the absolute prohibition of destructive impact upon return, the need for containment throughout the return phase of all returning hardware which directly contacted the target body or unsterilized material from the body, and the need for containment of any unsterilized samples collected and returned to Earth. Post-mission, there is a need to conduct timely analyses of the returned unsterilized samples, under strict containment, and using the most sensitive techniques. If any sign of the existence of a non-terrestrial replicating organism is found, the returned sample must remain contained unless treated by an effective sterilization procedure. Category V concerns are reflected in requirements that encompass those of Category IV plus a continuous monitoring of mission activities, studies, and research in sterilization procedures and containment techniques.

A.3 Biosafety Levels

(Descriptions and examples derived from http://www.cdc.gov/biosafety/publications/bmbl5/index.htm)

BSL	General Description	Example of Pathogen
1	Basic level of containment, no special barriers recommended. Suitable for handling organisms not known to be harmful to otherwise healthy people.	Canine hepatitis
2	Moderate level of containment, secondary barriers (hand washing sinks, waste decontamination) recommended. Suitable for handling organisms not transmissible via aerial routes.	Hepatitis B, HIV, Salmonella
3	High level of containment, secondary barriers include restricted access to the laboratories ventilation systems that minimize the release of aerosols. Appropriate for organisms that may cause serious or lethal infections.	Mycobacterium tuberculosis, St. Louis encephalitis virus
4	Advanced level of containment, requires laboratory workers' complete isolation (either in a suit or Class 3 Biological Safety Cabinet). Appropriate for dangerous or exotic agents that have a high likelihood of life-threatening illness or those for which there is no known treatment.	Marburg virus, Congo-Crimean hemorrhagic fever

A.4 Acronyms

Acronym	Definition
ALD	Analytical Laboratory Drawer
ASI	Agenzia Spaziale Italiana
BCB	Back Contamination Board
BEMA	Bogie Electro-Mechanical Assembly
BSL	Biosafety Level
CAPTEM	Curation and Analysis Planning Team for Extraterrestrial Materials
CERN	Conseil Européen pour la Recherche Nucléaire
CNES	Centre National d'Etudes Spatiales
COSPAR	Committee on Space Research
CR	Campaign Requirements
CSA	Canadian Space Agency
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center).
DHMR	Dry Heat Microbial Reduction
DNA	Deoxyribose Nucleic Acid
DS	Discipline Scientist
DSDP	Deep Sea Drilling Project
DSN	Deep Space Network
E2E-iSAG	End-to-End international Science Analysis Group
EDM	Entry, Descent, and Landing Demonstrator Module
ECSS	European Cooperation on Space Standardisation
ECU	European Currency Unit
EDL	Entry Descent and Landing
EEV	Earth Entry Vehicle, often referred to as ERC
EM	Engineering Model
ERC	Earth Re-entry Capsule
ERV	Earth Return Vehicle
ESA	European Space Agency
ESF	European Science Foundation
ESO	European Southern Observatory
FAR	Flight Acceptance Review
FPGA	Field Programmable Gate Array
FTIR	Fourier Transform Infrared
GC-MS	Gas Chromatography Mass Spectrometry
GEO	Group on Earth Observation

Acronym	Definition
GNC	Guidance, Navigation and Control
GR	Generic Requirement
H/W	Hardware
ICBC	Interagency Committee on Back Contamination (Apollo)
iMARS	International Mars Architecture for the Return of Samples
IMSI	International MSR Science Institute
IMEWG	International Mars Exploration Working Group
IODP	Integrated Ocean Drilling Program
ISO	International Organization for Standardization
ISS	International Space Station
IT	Information Technology
ITAR	International Traffic in Arms Regulation
JAXA	Japanese Aerospace Exploration Agency
JSC	Johnson Space Center
LRL	Lunar Receiving Laboratory
LSPET	Lunar Sample Preliminary Examination Team
MAV	Mars Ascent Vehicle
MEPAG	Mars Exploration Program Analysis Group
MMOD	Micrometeoroids and Orbital Debris
MMRTG	Multi Mission Radioisotope Thermoelectric Generator
MOI	Mars Orbit Insertion
MRSH	Mars Returned Sample Handling
MSL	Mars Science Laboratory
MSPET	Mars Sample Preliminary Examination Team
MSG	Meteorite Steering Group
MSR	Mars Sample Return
MWG	Meteorite Working Group
NASA	National Aeronautics and Space Administration (US)
ND-SAG	Next Decade Science Analysis Group
NRC	National Research Council (US)
OCP	Organic Contamination Panel
ODP	Ocean Drilling Program
OM	Orbiter Module
OS	Orbiting Sample
OSHS	Orbiting Sample Handling System
PAB	Public Advocacy Board
PDR	Preliminary Design Review
PDS	Planetary Data System
PI	Principal Investigator
PM	Propulsion Module

Acronym	Definition
PP	Planetary Protection
PRR	Preliminary Requirements Review
RdV	Rendezvous
RF	Radio Frequency
ROI	Region of Interest
SAB	Science Advisory Board
SAC	Sample Allocation Committee
SARB	Sample Allocation Review Board
SCF	Sample Curation Facility
SCR	Sample Caching Rover
SEDIS	Scientific Earth Drilling Information Service
SEM-EDS	Scanning Electron Microscopy Energy Dispersive X-ray Spectroscopy
SFR	Sample Fetch Rover
SEP	Solar Electric Propulsion
SR	Sample Return
SRF	Sample Return Facility
SRL	Sample Return Lander
SRO	Sample Return Orbiter
SRR	System Requirements Review
STEM	Scanning Transmission Electron Microscopy
TBD	To Be Determined
TPS	Thermal Protection System
TRL	Technology Readiness Level
TVAC	Thermal Vacuum
UHF	Ultra High Frequency
UHV	Ultra High Vacuum
V&V	Verification and Validation

A.5 Technology

A.5.1 Sample Caching Rover Element Technologies

Technology domain	Technology title	Status in 2015	Next steps	Agency
Autonomous navigation	Algorithms for rover full autonomous navigation	Successfully tested on CNES Mars ground with a rover remotely controlled from ESTEC.	Further test planned in 2015 with improved system and modified Mars terrain.	CNES
Autonomous Operations	Autonomous surface operations	Autonomy in research phase.	Develop autonomy goals and develop algorithms for planned operations. Test in relevant environment.	CSA, NASA
Deep Drilling	Sample acquisition & transfer system	Down to 1 m drill prototype developed & demonstrated in analogue. DTAV prototype in development.	Currently working on testing of the drilling mechanism in lunar simulant. Mars like material was carried in previous testing. Sample capture and transfer system to be further refined.	CSA
Dexterous Robotics for Sample retrieval	Dexterous manipulator/sample cache capture mechanism	Manipulator concept study in progress, small manipulator prototypes deployed in analogues, dexterous tools and know-how.	Need to identify specific requirements to start building manipulator for the mission based on lessons learned.	CSA
Mobility	Fast traverse	Developed and proven in testbed.	Develop flight implementation, test in relevant environment.	ESA/ NASA
Mobility Sensors	Camera sensors	Building camera sensor for ExoMars.	Integrated camera with on-board advance processing for visual odometry.	CSA
Mobility Sensors	LiDAR for navigation	Scanning LIDAR prototypes developed up to testing in TVAC, concept study for compact LiDAR in progress.	Currently working on reducing LIDAR size and mass, next step to reach a TRL 4 by 2016.	CSA

Technology domain	Technology title	Status in 2015	Next steps	Agency
Planetary Protection	Forward planetary protection	Kill, clean and verify protocols. Dry heat sterilization methods.	Develop specific implementation criteria, develop protocols and procedures to meet criteria.	ESA/ NASA
Planetary Protection	Round trip planetary protection/ contamination control	Kill, clean and verify protocols. Dry heat sterilization methods.	Potential technology demonstration with M2020.	NASA
Planetary Protection	Biobarriers for sample cleanliness	Biobarriers to maintain cleanliness of the sampling system during assembly, cruise and surface operations.	Potential technology demonstration with M2020.	NASA
Precision Landing	Terrain relative navigation	Algorithms developed, tested in simulations.	Test Algorithms in field test environment, develop flight software and test.	NASA
Precision Landing	Hazard detection	Developed and tested in a testbed environment.	Develop flight implementation, test in relevant environment.	CSA, NASA
Sample Collection	Sample coring	Coring drills in development.	Validation in relevant environment.	CSA, NASA
Sample collection	Deep drill & sample collection	EQM completion (fully qualified for ExoMars mission	Qualification test campaign completion.	ASI/ ESA
Sample handling	Sample Preparation and Distribution system	EQM completion (fully qualified for ExoMars mission	Qualification test campaign completion.	ASI/ ESA
Sample Integrity	Sample sealing	Developed options for sealing sample tubes. Proven techniques to achieve leakage rate requirements.	Develop preferred implementation approach, test in relevant environment.	ESA/ NASA

Technology domain	Technology title	Status in 2015	Next steps	Agency
Telecommunica-tions	Telecommunica-tions system for rover/lander	Phase 0 Study aimed at developing an architecture and requirements for a Mars 2020 rover high gain antenna, rover direct to Earth antenna, rover emulation prototype built.	Develop preferred architecture, test in relevant environment.	CSA/ NASA
Sample handling & transfer	Sample encapsu-lation	Research of sample core transfers, one bit per sample encapsulation, reusable core bits with sample tubes.	Develop preferred approach, test in relevant environment.	NASA

A.5.2 Sample Return Lander element technologies

Technology domain	Technology title	Status in 2015	Next steps	Agency
Atmospheric entry	Sensor for the measurement of the Integrated radiated flux on the backshell of large entry capsule. Radiated fluxes at the back are a design driver for the backshell TPS.	Part of the COMARS+ experiment on the ExoMars 2016 EDM - FM provided and integrated in EDM.		CNES / DLR
Autonomous Operations	Autonomous surface operations	Autonomy in research phase.	Develop autonomy goals and develop algorithms for planned operations. Test in relevant environment.	NASA
Autonomous Operations	Test and validation techniques	Ongoing development of a core environment and infrastructures for End to end validation of autonomous systems and technologies.	NA - Objective is to offer a highly performing facility to demonstrate on-ground complex autonomy systems and associated technologies from unit to mission levels.	ESA
Dexterous Robotics for Sample retrieval	Dexterous manipulator/sample cache capture mechanism	Manipulator concept study in progress, small manipulator prototypes deployed in analogues, dexterous tools and know-how.	Need to identify specific requirements to start building manipulator for the mission based on lessons learned.	CSA
Mars Ascent Vehicle	MAV architecture	MAV architecture options under study. Specific technology areas in test (shock survivability, temperature sensitivity).	Develop preferred architecture, test in relevant environment.	NASA
Mobility	Fast traverse	Developed and proven in testbed.	Develop flight implementation, test in relevant environment.	NASA/ ESA

Technology domain	Technology title	Status in 2015	Next steps	Agency
Mobility	Mechanisms & technologies for very low temperatures	Breadboarding and test of drive mechanism components.	Test of fully integrated drive chain in relevant environment.	ESA
Mobility	Fast navigation	Image processing implemented in FPGA not space qualified yet.	Implementation and test of image processing and navigation algorithms in flight qualified hardware and test in field trials using integrated systems (sensors, electronic boards, mobile platform).	ESA
Mobility Platform	Sample return rover	Micro-rover and medium rovers used in analogue deployments, drive train development on going prime contractor experience on ExoMars rover (BEMA). Drivetrain being tested in lunar conditions.	Drivetrain DTVAC testing, optimization and testing to come, small rover between micro and medium by 2016.	CSA
Mobility Sensors	Camera Sensors	Building camera sensor for ExoMars.	Integrated camera with on-board advance processing for visual odometry.	CSA
Mobility Sensors	LiDAR for navigation	Scanning LIDAR prototypes developed up to testing in TVAC, concept study for compact LiDAR in progress, compact LiDAR.	Currently working on reducing LIDAR size and mass, next step to reach TRL 4 by 2016.	CSA
Orbiting Sample Container	Sample encapsulation	Architecture options under study. Breadboard manufactured and tested for one given architecture.	Develop preferred encapsulation approach, test in relevant environment.	NASA/ ESA
Planetary Protection	Forward planetary protection	Kill, clean and verify protocols. Dry heat sterilization methods.	Develop specific implementation criteria, develop protocols and procedures to meet criteria.	NASA/ ESA

Technology domain	Technology title	Status in 2015	Next steps	Agency
Power	Low temperature batteries	Test of Li-Ion batteries based on low temperature charging technologies. Activity scheduled in 2015 for breadboarding and test of battery assembly at low temperature (including all mechanical test).		ESA
Precision Landing	Terrain relative navigation	Algorithms developed, tested in simulations & partly in field tests.	Test algorithms in field test environment, develop flight software and test.	NASA / ESA
Precision Landing	Hazard detection	Developed and tested in a testbed environment.	Develop flight implementation, test in relevant environment.	NASA / ESA
Sample collection	Atmospheric sample collection	Research level investigations of sampling approaches.		NASA
Sample Handling	Sample transfer and handling	Developing architectures for sample tube transfer. Detailed sample transfer approach to be developed, specific technologies to be identified and matured.	Develop preferred approach, develop proto-flight test units and test in relevant environments.	NASA
Sample Handling	Robotic arm for fetch rover	Breadboard of a robotic arm suitable for the fetch rover.	Buildup and test of an EM in relevant environment.	ESA
Telecommunications	Telecommunications system for rover/lander	Phase 0 Study aimed at developing an architecture and requirements for a Mars 2020 rover high gain antenna rover direct to Earth antenna rover emulation prototype built.	Develop preferred architecture, test in relevant environment.	CSA
Telecommunications	Telecommunications system for rover/lander	Development of a miniaturised dual UHF/X band transponder concept. Activity scheduled in 2015 to develop and test a breadboard.	Buildup and test of an EM (including antenna) in relevant environment.	ESA

A.5.3 Sample Return Orbiter element technologies

Technology domain	Technology title	Status in 2015	Next steps	Agency
Autonomous aerobraking	Enhanced aerobraking autonomy and robustness	Robust aerobraking activity allows enhanced autonomy and "agressiveness" of aerobraking to minimise the aerobraking phase duration (~1 year).	End-to-end simulator including operations, possibly some hardware development (e.g. drag flaps, heat flux sensors), TBD when aerobraking concept is matured.	ESA
Back Planetary Protection	Bio-sealing, including "break-the-chain," and monitoring	ESA breadboard of triple redundant seal & break-the-chain technique tested with promising results. On-going activity with enhanced breadboarding & tests.	Build-up and test of an EM, interfaced with the sample transfer system.	ESA / NASA
Earth Entry Vehicle / Earth Re-entry Capsule	Thermal protection system	NASA PICA material flight-tested; ESA material: Material produced and fully tested at representative heat fluxes, also including limited number of hypervelocity impact test.	Not possible to test full-scale model in high enthalpy facilities. Tests on subscale samples together with high fidelity simulations and build-up of a full scale model are deemed sufficient for starting project implementation.	ESA / NASA
Earth Entry Vehicle / Earth Re-entry Capsule	Crushable structure	Crushable materials have been tested and down-selected. Crushable structure breadboard to be tested in 2015 with 2 different crushable materials.	Build-up and test of a fully representative STM.	ESA
Earth Entry Vehicle / Earth Re-entry Capsule	Aeroshape (for no-parachute designs)	Hayabusa shape (downscaled) with modified backshell successfully tested at all regimes (supersonic to low subsonic). End to end drop test from balloon with three different shapes of footprint & ERC size are foreseen in summer 2015.	TRL 5 deemed sufficient (i.e., no need for a full scale end to end drop test), provided the aerodynamic database proves to be robust for larger scale.	ESA
Earth Entry Vehicle / Earth Re-entry Capsule	Shock resistant RF beacon	A breadboard activity started in 2015. Test on batteries already showed promising results.	Following the breadboard activity, build-up and test of a fully integrated EM at correct scale (beacon + antenna + battery).	ESA

Technology domain	Technology title	Status in 2015	Next steps	Agency
Earth Entry Vehicle / Earth Re-entry Capsule	MMOD protection and detection cover	Activity in 2015 to reach TRL 3-4. Follow-on activity to be started in 2015, including hyper-velocity impact tests on the integrated MMOD shield and TPS front cover, and damaged TPS high enthalpy testing.	To be assessed at completion of the integrated protection cover and TPS shield activity.	ESA / NASA
OS handling and transfer mechanisms	Mechanism suite to transfer sample	Conceptual studies.	Build-up and test of an EM, interfaced with the bioseal-ing system.	ESA / NASA
Planetary Protection	Sample quality control	Sealing the sample cache to insure surface con-tamination is completely encapsulated.	Architecture studies.	NASA
Rendezvous and Capture	Rendezvous GNC software	Software validation with hardware in the loop & dynamic test bench.	Hardware in the loop tests with sensors.	ESA / NASA
Rendezvous and Capture	RF sensor	Breadboard & test of 2 possible concepts (1-way and 2-ways Doppler).	Enhanced breadboarding (incl. antenna), build-up of an EM and far-range test.	ESA
Rendezvous and Capture	Camera sensors	Breadboards for vision-based navigation.	Build-up and test of an EM, including image processing.	ESA
Rendezvous and Capture	Capture mechanism	Sample canister capture mechanism breadboard tested in 0 g environment with a parabolic flight test.	-	ESA / NASA
Rendezvous and Capture	Proximity and docking sensors (LIDaR)	TRiDAR rendezvous sensor flew on Space Shuttle, commercial docking sensor on Cygus capsule, Next generation TriDARTVAC validated, On-going Phase 0 for next generation sensor on ISS.	Current objective is for a life of 2-5 years in LEO, need to be further tested. Minia-turisation considered, more testing and studies required for an adaptation to a MSL mission.	CSA

Technology domain	Technology title	Status in 2015	Next steps	Agency
Sample container rendezvous in Mars orbit	Autonomous tracking of a non-cooperative target with optical camera, later with a LIDAR.	During the Prisma formation flying demonstration mission in LEO, a non-cooperative target was approached with an autonomous tracking satellite from 10 km to 50 m, with sub m precision, with the only information of an optical visible camera.	For debris capture or in-orbit refuelling, CNES is currently performing a preliminary study of an extensive demonstration mission that would validate the full rendezvous down to the last meter.	SSC / CNES
SEP	Solar electric propulsion	SEP technologies have been developed to enable a range of SRO options.	Technology mature for most concepts.	NASA

A.5.3 Sample Return Orbiter element technologies

Technology domain	Technology title	Status in 2015	Next steps	Agency
Planetary Protection	Sterilization techniques (and verification) for optimal science.	Multiple sterilisation techniques exist. Different techniques have impact on specific sample science. An approved protocol for returned samples is needed.	Study needed to gain consensus on approved techniques. Laboratory validation may be required.	NASA
Robotic manipulation	Manipulation systems for sample handling in a Sample Receiving Facility	Three years ESA activity to be started in 2015.	Then an EM should be built and tested.	ESA
Sample Containment	Double-wall containment vessels	Concepts developed during industry studies. Standard glove-box methods maybe adaptable to this implementation. Implementation has not been demonstrated.	Study needed to identify appropriate implementation. Prototype development and validation is needed.	NASA / ESA
Sample Containment	Gloves and glove ports for double-walled containment vessels	Single wall glovebiox implementation routinely used. Double-walled development needed. Current materials may not meet organic cleanliness requirements.	Industry survey needed. Materials research maybe needed. Need prototypes developed and validated.	NASA
Sample Curation	Cleaning and contamination control of items exposed to samples	Meeting MSR contamination control requirements is challenging. Techniques have been implemented for prior sample returns and used in the JSC Astromaterials Laboratories.	Study needed to identify containers, sample preparation processes, tools, and instrumentation needed for MSR. Cleanliness and contamination control needs to be validated. Techniques may require further research.	NASA

Technology domain	Technology title	Status in 2015	Next steps	Agency
Sample Handling	Dextrous ultra-clean robotic sample handling/ manipulation	Clean robotics are used in the semiconductor and medical industries.	Industry survey studies needed. Development of testbed is needed. Validation of cleanliness is required. Maintainability processes needs to be verified.	NASA
Sample Handling	Portable BSL-4-level sample containers with internal manipulation and window for remote instruments	Containers for transporting BSL-4 material exist. Specialized containers meeting cleanliness requirements and with means of remote sensing science is only a concept.	Needs for types of analysis access windows and manipulation needs to be studied. Prototypes need to be developed. Cleanliness, BSL-4-level containment and sample analysis access needs to be validated.	NASA
Sample Handling	Laser welding for robotic sealing of Mars contaminated items inside a container	Tests done. Process too challenging from a robotic point of view.	Use of electron beam welding process.	CNES
Sample Handling	Miniaturized Extraterrestrial Sample Holder containing samples in BSL4 conditions and allowing sample characterisation and analysis through specific windows.	Prototype successfully tested and principle patented.		CNES
Sample Instruments	Science instrument adaptation to operate in or interface with ultra-clean BSL-4 environment	Instruments developed for space, in-laboratory and some with interfaces with BSL-4 are in practice. Suitability for instruments needed for PP test protocol and preliminary science has not been studied.	Study to identify instruments needed. Survey of suitability. Prototype as needed to validate cleanliness or port access to samples.	NASA

IMAGE

Faulted Layers in Collapse Pits. This image shows a set of coalesced collapse pits in western Valles Marineris. Fine layers are exposed in the walls of the pits, and in some places those layers are displaced by faults.

Image credit: NASA/JPL-Caltech/Univ. of Arizona